Advances in Technology

Seated, *left to right,* are the panel moderator Jacob Neufeld and Dr. Donald R. Baucom. Standing *left to right* are Drs. Richard P. Hallion and Rick W. Sturdevant.

Military Power and the Revolution in Military Affairs

Richard P. Hallion

It is a pleasure to have the opportunity to speak to you all today on the subject of "Military Power and the Revolution in Military Affairs" and to examine just what that means, including its implications for the modern world. There are many ways in which we can address this subject, and my perspective will be largely from the perspective of modern joint service aerospace power. To look at the RMA and its future implications demands that we understand the place and pace of technology and, in particular, aerospace power, within modern military affairs.

Let's start with some quotes from through the years, beginning with two from the early part of this century:

> In our days wars are won not by mere enthusiasm but by technical superiority.—V.I. Lenin, 1918

> Victory smiles upon those who anticipate changes in the character of war, not upon those who wait to adapt themselves after the changes occur.—Giulio Douhet, *The Command of the Air,* 1921

The former is a cautionary one, for it shows that one of democracy's most implacable enemies had a pretty good grasp on the importance of technology investment at a time when the kinds of high-technology capabilities that modern nation-states today possess were only at best the dreams of visionaries. The second is what probably many think must be an obligatory requirement for airmen to root their thought in the hallowed precepts of Douhet—but the truth of that statement should not be underestimated, particularly in the present day, when there is such an international debate on the character and merits of aerospace power.

For my part, my favorite quote is quite different, and comes from that great theorist and student of warfare, Maj. Gen. J.F.C. Fuller, writing in his seminal *Armament and History,* in 1945:

> The weapon of superior reach or range should be looked upon as the fulcrum of combined tactics. Thus, should a group of fighters

> be armed with bows, spears and swords, it is around the arrow that tactics should be shaped; if with cannons, muskets, and pikes, then around the cannon; *and if with aircraft, artillery, and rifles, then around the airplane.*

Fuller's were strong words for 1945, but quite logical if one considers what the world had witnessed in air power development to that time, namely that the reach of air power forces—now aerospace forces—constituted the vital factor in military affairs.

Aerospace Power, Technology, and Military Transformation

Surely today, in an era of a much-discussed Revolution in Military Affairs, such sentiments would hardly be surprising, given the revolutionary character of high technology and its impact on all military affairs, not just aerospace. Or would they? Unfortunately, as the following three quotes indicate, such is far from the case. Not only is there no agreement as to where technology fits with military affairs, there is not even a consensus among experts whether or not an RMA is, in fact, taking place!

> War is a matter of heart and will first; weaponry and technology second.—Gen. Gordon R. Sullivan and Lt. Col. James M. Dubik, "Land Warfare in the 21st Century," Strategic Studies Institute, U.S. Army War College, Feb. 1993

> The ingredients for a transformation of war may well have become visible in the Gulf War, but if a revolution is to occur someone will have to make it.—Eliot A. Cohen and Thomas A. Keaney, *Gulf War Air Power Survey Summary Report,* p. 251, 1993

> Technology and air power are integrally and synergistically related. . . . Air power is the result of technology. Man has been able to fight with his hands or simple implements and sail on water using wind or muscle power for millennia, but flight required advanced technology. As a consequence of this immutable fact, air power has enjoyed a synergistic relationship with technology not common to surface forces, and this is part of the airman's culture.—Col. Phillip Meilinger, USAF, *Ten Propositions Regarding Air Power,* 1995

What is the actual situation? One can only offer one's own views. I believe that the Western world in particular is clearly in the midst of an ongoing "Revolution in Military Affairs," one that is largely technologically driven and characterized by a number of discrete factors representing, first and foremost, *the confluence of the aerospace and the electronic revolutions,* the two great revolutions that, together with the atomic revolution, utterly transformed science, technology, and society in this century. Coming out of this confluence are a number of attributes, four that I think are particularly important are:

—*increasing reliance on precision systems* (the precision of finding, fixing, and attacking, but also the precision of industry, in manufacturing techniques and design).

—*increasing information exploitation* (the product of overhead atmospheric systems and space platforms, but also the product of knowledge gathering and exploiting systems).

—*increasing communication availability* (a direct beneficiary of both the aerospace and electronic revolutions, which transforms understanding, plans, and operations alike, via sophisticated systems and architectures).

—*rapidly advancing predictive methods and materials science* (which enables the development of new and radically transforming tools, weapons, systems, and vehicles having greater operational effectiveness and greater readiness).

I would also suggest that this RMA has been a very long time coming and, in fact, that it dates to the middle of the Second World War. Further, it reflects a larger transformation, and that is the shift over the last ninety years from two-dimensionally constrained warfare with which the century began to three-dimensional warfare involving aerospace systems and submarines. This 2D to 3D shift has increasingly seen surface forces and surface movement hindered, constrained, and now, increasingly, held hostage to the wishes and intent of the 3D attacker. Today, what's happening *above or below* the surface is often far more important than what's happening on the surface itself.

A review of some very-broad-stroke significant chronological milestones in military aerospace history in this century points to this technologically driven transformation, all the more remarkable because of its rapidity (remember, the baseline dates are the Wright brothers' first flight at Kitty Hawk in 1903 and Robert Goddard's first liquid-fuel rocket flight in 1926):

1908: First military airplane flies.
1911: Aircraft attack against surface forces.
1914: Submarine attack against naval forces.
1918: Aircraft carrier attack against land targets.
1936: First militarily significant airlift of combat forces.
1939: First jet engine flown.
1940: First use of integrated air defense systems.
1943: Precision Guided Munition attacks against surface forces.
1944: Era of strategic cruise and ballistic missile attack begins.
1949: First air-refueled around-the-world flight.
1957: First earth satellite.
1958: Beginnings of attack-and-troop-lift helicopter assault.
1960: Era of surface-to-air missile combat operations begins.
1960: First reconnaissance satellite orbited.

1961: First manned orbital flight.
1968: High bypass ratio turbofan enters service.
1969: *Apollo XI* mission to the Moon.
1983: First operational stealth aircraft.
1991: Submarine missile attack against land targets.
1991: Space-based cueing of ground-based aerospace defenses.

View and Mobility

Aerospace power possesses two unique qualities that work to enhance its effectiveness as a power projection tool and an instrument of national policy: view and mobility. The first, *view*, is a traditional virtue throughout military history, and the aerospace revolution of this century has greatly increased its importance. The key to view is height: with height comes a natural vantage point, and with view comes awareness and the opportunity (hopefully) for informed decision-making leading to decisive action. From being restricted to the highest hills, armies came to rely upon tethered observation balloons; then, in the twentieth century, to airborne reconnaissance aircraft: the first military airplane, the Wright 1908 Military Flyer, was designed for reconnaissance. With the spaceflight revolution, view expanded in this century from battlefield to theater and now to global dimensions; thanks to advances in communications, the products of atmospheric and space reconnaissance systems are, for the most part, the primary means whereby national leaderships learn about global developments and then formulate plans to deal with them.

The second quality, the inherent rapid *mobility* of aerospace forces, has worked its own profound transformation of military affairs, as evident in operations from the Berlin Airlift of 1948 through the Yom Kippur War's Emergency Airlift, Desert Shield and Desert Storm, and on to the various crises we face today. Mobility has been an important factor in military affairs since Sun Tzu penned "Rapidity is the essence of war." In a century in which surface mobility rates have generally stagnated, the rate of mobility for joint service aerospace forces now approaches 500+ knots, ensuring global on-scene presence within hours, not days or weeks.

This inherent aerospace mobility advantage, first visible in the era of the piston engine but fulfilled only in the era of the high-performance gas turbine engine, has transformed the meaning of "crisis response." In the American case, it is greatly assisted by air refueling and space support (such as navigation, intelligence, weather, and communications). For nations able to deploy air mobility forces, those forces furnish tremendous innate flexibility: what might be termed the "bombs, bread, or both" options for delivery. Today rapid-deploying aerospace forces are to the world community what ships were to the nineteenth century: not without reason Britain's Foreign Secretary referred to "my 600 knot gunboats" as the RAF deployed its Tornadoes to the Gulf in 1990 prior to Desert Storm.

Any cursory examination reveals that there are a plethora of light and medium military transports available for the world's air forces, best exemplified, perhaps, by the ubiquitous Hercules. Additionally, given the capabilities of modern civilian widebody jet airliners, a relatively modest investment can buy significant "off the shelf" power and presence-projection capabilities using freighter derivatives of widebody commercial aircraft such as the Airbus family or the Boeing 767. (Canada has followed just such a course with its A–310-derived CC–150 Polaris program. Great Britain did the same with its Lockheed TriStar tanker-transport aircraft, as did the United States with the KC–10 Extender.) Special-purpose high-capacity jet airlifters typified by the C–141, C–5, or C–17 family are a different matter, but contract airlift (typified by the growing market today for high-capacity widebodies such as the An–124) can ease the access problem for nations lacking such craft. Jet airlifter "rental" can significantly enhance the airlift capabilities of larger nations and substitute for the lack of organic air mobility forces for smaller ones, though it is far less desirable for any nation seeking to undertake routine power and presence operations at a distance, particularly since the nation of origin may be unwilling to contract out its aircraft due to its own political goals and objectives. One special arrangement that has worked very well for the United States—particularly in the Gulf crisis—is the Civil Reserve Air Fleet, the so-called CRAF, the result of a partnership agreement between various American airline companies and the Department of Defense.

Since the 1950s, air refueling has been a significant mobility enabler for the world's larger air forces. Their substantial investment in air refueling technology has generated a consequent dramatic improvement in their ability to deploy forces at long range. Notable examples include both the U.S. Air Force's Tactical and Strategic Air Commands, and Military Airlift Command (now Air Combat Command and Air Mobility Command) and the British V-bomber force. The payoff of this investment has been evident in combat experience ranging from the RAF's Black Buck mission during the Falklands War and Operation El Dorado Canyon in 1986 to, most recently, the experience of the Gulf War and post-Gulf deployments and exercises, humanitarian airlift and relief missions, and NATO air operations over Bosnia. Even a relatively small investment in air refueling capability can have profound implications for deploying combat forces at long range, as was demonstrated by the Israeli air force during long-range counterterror operations in the 1980s.

Critics and the Reality of Aerospace Power

Understandably, aerospace power has had its critics, and this presentation is not to imply that aerospace power is the solution for all problems and situations. Nevertheless, it is fair to say that, given its impact on international affairs, aerospace power has consistently been underestimated by its critics, a tendency dating to the dawn of military aviation. For example, on the eve of the First World War, while lecturing to students at the British Army Staff College at Camberley, Gen. Douglas Haig bluntly stated:

> I hope none of you gentlemen so foolish as to think that aeroplanes will be usefully employed for reconnaissance from the air. There is only one way for a commander to get information by reconnaissance and that is by the use of cavalry.

Within months, of course, aerial reconnaissance had helped shape the outcome of both the Battle of Tannenberg and the Battle of the Marne, and proven its utter importance in military affairs. Speaking at the dawn of aviation, Haig might be somewhat forgiven his skepticism. But more distressing are critics today who seemingly argue that air power somehow has yet to fulfill its promise over the battlefield. (In fact, since the Korean War, not a single U.S. Army soldier has perished from enemy air attack, a tribute to the dominance of the U.S. Air Force over its foes.)

Such skepticism was rampant on the eve of the Gulf War of 1991. As the Gulf crisis built, Saddam Hussein had remarked that "The United States relies on the Air Force and the Air Force has never been the decisive factor in the history of wars." Only nine percent of the weapons employed by coalition air forces against Iraq were precision weapons, yet by the midst of the war, with nightly television evidence of blown-up headquarters, shattered aircraft shelters, cruise missiles finding their way to their targets with almost a dainty accuracy, and burning tanks, Chairman of the Joint Chiefs of Staff Gen. Colin Powell was confidently testifying before Congress that:

> Air power is the decisive arm so far, and I expect it will be the decisive arm into the end of the campaign, even if ground forces and amphibious forces are added to the equation. . . . If anything, I expect air power to be even more decisive in the days and weeks ahead.

After the war, President George Bush was more succinct when he stated "Gulf Lesson One is the value of air power," and Secretary of Defense Dick Cheney was equally blunt when, in a news interview, he remarked "The air campaign was decisive."

Such continued to be true in Bosnia, where NATO aerospace power proved crucial to halting a war and setting the stage for building a peace. Here, the overwhelming percentage—98 percent—of American ordnance was precision weaponry. At the end of NATO's Bosnian air campaign of 1995, former Assistant Secretary of State Richard Holbrooke stated: "One of the great things that people should have learned from [the NATO air campaign in Bosnia] is that there are times when air power—not backed up by ground troops—can make a difference."

Slobodan Milosevic, on the receiving end of NATO power, likewise understood the leverage of modern air attack. While dining at the Air Force Museum during the Dayton Peace Accords, the Serb leader wistfully looked at a cruise missile dangling overhead and remarked—within earshot of Richard Holbrooke—"So much damage from such a little thing."

Modern Aerospace Power: A Case of "Back to the Future"

The transforming nature of air power, evidence of the leverage of technology, is not something of recent origin, as a cursory review of military history illustrates. Writing after the First World War, Maj. Gen. Heinz Guderian noted in his book *Achtung Panzer* (1937) that:

> [in World War I] aircraft became an offensive weapon of the first order, distinguished by their great speed, range and effect on target. If their initial development experienced a check when hostilities came to an end in 1918, they had already shown their potential clearly enough to those who were on the receiving end . . . we do not have to be out and out disciples of Douhet to be persuaded of the great significance of air forces for a future war, and *to go on from there to explore how success in the air could be exploited for ground warfare, which would in turn consolidate the aerial victory.*

Post-"Great War" experience, even in this relatively primitive era of air power employment, supported those who saw in the airplane the embodiment of a revolution in military affairs. Writing after the Spanish Civil War, where air power had been employed in all its many roles, from battlefield support to reconnaissance, air mobility, and strategic attack, the Czech-born military analyst (and Spanish war veteran) Ferdinand Miksche wrote: "The air force has become the hammer of modern warfare on land. . . . Aviation gives modern battle a third dimension . . . modern battle is the fight for cubic space."

A plethora of military quotes from the Second World War attest to air power's significance, including from Prime Minister Winston Churchill's famous and oft-quoted "Never in the field of human conflict was so much owed by so many to so few" (from a 1940 speech in Parliament praising the victory of the Royal Air Force over the Luftwaffe in the Battle of Britain) to Field Marshal Erwin "The Desert Fox" Rommel's reflective lamentations after Alam Halfa in the Western Desert in 1942 that:

> Anyone who has to fight, even with the most modern weapons, against an enemy in complete command of the air, fights like a savage against modern European troops, under the same handicaps and with the same chances of success. . . . *In every battle to come the strength of the Anglo-American air force was to be the deciding factor.*

The Normandy campaign offers a particularly juicy selection of air power assessments, from victor and (tellingly) the vanquished. Responding to a question from his son John, a newly graduated Army lieutenant fresh out of West Point, Dwight Eisenhower surveyed the exposed logistics and troop concentrations at Normandy after the invasion and stated emphatically, "If I didn't have air supremacy, I wouldn't be here." At nearly the same time, morosely, Field Marshal Erwin Rommel wrote to his wife that: "The enemy's air superiority has a very grave effect on our movements. There's simply no answer to it." Vice Admiral Friedrich Ruge, his naval aide, penned, "Utilization of the Anglo-American air forces is the modern type of warfare, turning the flank not from the side but from above." More importantly, the German commander in the west, Field Marshal Hans Guenther von Kluge, wrote to Hitler that: "In the face of the total enemy air superiority, we can adopt no tactics to compensate for the annihilating power of air except to retire from the battlefield."

In a strategic sense, both senior Nazi and Japanese leaders had little doubt what was causing them their greatest problems in 1944 and 1945. Reflecting on the defeat of the Third Reich, former Nazi armaments minister Albert Speer wrote in his memoirs (1970) that "[Bombing of oil targets] meant the end of German armaments production." The Japanese leadership was equally blunt. Responding to a postwar interrogator, Prince Fumimaro Konoye stated "The thing that brought about the determination [for Japan] to make peace was the prolonged bombing by the B-29s."

In sum, even in the days of relatively immature air power, guided largely by the human eye, and with aircraft woefully deficient in range, speed, and payload compared to today's technology, air power had a surprising and often decisive impact on military affairs. In the precision engagement era, what has changed most dramatically has been the *time scale* and *level of effort* required to achieve such effects. Today, for example, we do not speak of *sorties required to destroy a target,* we speak of the *number of targets destroyed per sortie.*

So, When Did the RMA *Really* Begin?

The record of air power through 1945 argues powerfully that the so-called "Revolution in Military Affairs" is not only long-standing, but that it dates back over a half-century, to the midst of the Second World War. In that war, traditional patterns of surface conflict on sea and on land were shattered forever. At sea, 77 percent of German ships were sunk by Royal Air Force air attack; 47 percent of German U-boats were sunk by Allied air attack, and (while 48 percent were sunk by submarines) 45 percent of all Japanese naval and merchant vessels were sunk by land- and sea-based air attackers. (In a foretelling of the Falklands War and the Gulf, rudimentary precision guided missiles and torpedoes sunk some of these vessels; for their part, the Germans employed an increasingly wide range of precision weapons against Allied shipping, with occasional disastrous results for their victims.) In short, the 3D attacker triumphed over the 2D surface opponent.

On land, air attack increasingly hindered and crippled the movement of surface forces, most evident in the clear terrain of the Western Desert, but also present in Europe and the Pacific. German road signs warned drivers not to use certain roads due to Allied “deep flyers” and “Jabos” (fighter-bombers) on both the Western and Eastern fronts. When one thinks of the length of a high summer day in 1944, after the Allied air forces already were roaming over much of Germany and Occupied Europe, the implications for time-warfare implicit in such signs is clearly evident. Direct air attack hindered the mobility of German forces so badly that one German commander in Italy compared himself to a chess player able to make only one move to an opponent’s three. From 1943 onward, according to senior German medical personnel and records, Allied air attacks were the *primary* means whereby the German *Wehrmacht* suffered casualties on its fighting fronts, followed by artillery as a distant second, and then all other weapons. This trend in casualties continued and the disparity between air attack and other forms of attack grew even more pronounced over 1944 and 1945.

In fact, for the United States, this trend of inflicting losses and material destruction primarily through air attack continued into the postwar years for Korea, Vietnam, the Gulf, Bosnia, and other, lesser, contingencies. It may be considered, as some have termed it, a “New American Way of War,” but it is less recent revolutionary than older evolutionary (with its roots in an earlier revolutionary period). In particular, air attack directed against land forces has been especially powerful in blunting and destroying opponents on the offensive, whether in older experience—such as confronting Rommel in the Western Desert, or Nazi armored forces trying to split the Normandy invasion at Mortain, or at the Bulge (where German commanders credited Allied fighter attacks on fuel trucks and supplies as being the decisive factor in halting their drive), in the opening and closing stages of the Korean War (where 75 percent of tanks, 72 percent of artillery, and 81 percent of trucks were destroyed from the air), and confronting the 1972 North Vietnamese Spring Invasion—or, more recently, in destroying the Khafji offensive of Saddam Hussein in 1991.

Aerospace Power: The Tool of Choice

It is surprising, given its record, that aerospace power advocates should still have to spend as much time as they do arguing the merits of three-dimensional war. Clearly, the RMA is here, has been for a long time, is largely an aerospace revolution, and must continue—if for no other reason than that aerospace forces are the most *responsive, flexible,* and, if need be, *lethal* and *devastating* form of power projection across the spectrum of conflict. These forces are by no means limited just to those employed by air forces. Each service has, to a greater or lesser degree, a commitment to use its own organic air-or-aerospace power resources, be they maritime patrol aircraft, attack and troop-lift helicopters, land-based long-range aircraft, and battlefield rocket artillery systems, and that service-specific aerospace power can often be formidable. (In the Gulf War, for example, U.S. Army AH–64A Apache helicopter gunships were credited with the destruction of nearly 950 tanks, personnel carriers, and miscellaneous vehicles.)

Understandably, then, aerospace forces are increasingly the most commonly employed military tool for crisis intervention for advanced nations, relied upon by national and international leaders. In the American experience, it may be carrier battle groups, air expeditionary forces, or operations of our total force Guard and Reserve components. Given this situation, for all services, how they structure and operate their aerospace forces is now of critical importance and will continue to be so in the future. Nowhere is there more interest, study, and, indeed, controversy than in the issue of joint operations between traditional surface forces and their aerospace brethren.

Yet even here has been real progress in the recognition, at least, that aerospace warfare has changed the nature and character of war, even if there is often profound disagreement on just how far that transformation and change goes. Reflecting this are the realities of defense procurement, where, for most NATO nations, procurement of traditional "2D" land warfare systems (tanks, vehicles, and infantry-support equipment) has been sharply reduced, while procurement and modernization of "3D" aviation (especially helicopter) and artillery systems has proliferated. To give but one example, in the ten years from 1986 to 1996, the number of tanks in the British Army declined from 1,030 to 500, and personnel from 163,000 to 116,000, while British Army aircraft increased from 323 to 391.

Aerospace Power and Minimizing the Risk of the Close Fight

The recognition by political and diplomatic leaders of aerospace power as the tool of choice has profound implications for how military services organize, train, equip, and fight in the joint and combined arena. Given rapid advances in the ability of aerospace forces to undertake precision targeting, tracking, and engagement, opportunities exist to exploit aerospace power's leverage to overcome the traditional problem of simultaneously trying to halt an enemy force on the move while attacking its means of waging war deep within the enemy heartland.

The authors of *The New Calculus,* a perceptive 1993 RAND study, concluded that:

> The calculus [of warfare] has changed and airpower's ability to contribute to the joint battle has increased. Not only can modern air

> power arrive quickly where needed, it has become far more lethal in conventional operations. Equipped with advanced munitions . . . and directed by modern C^3I systems, air power has the potential to destroy enemy ground forces either on the move or in defensive positions at a high rate while concurrently destroying vital elements of the enemy's war-fighting infrastructure. In short, the mobility, lethality, and survivability of air power makes it well suited to the needs of rapidly developing regional conflicts.

Traditionally, the greatest source of casualties in land combat operations have been from close combat; it is here not only that enemy fires are most intensive, but that there is the greatest risk of friendly fire incidents as well. In the Gulf War, for example, friendly fire casualties constituted 18 percent of all U.S. battle casualties and 24 percent of all U.S. deaths. (Despite much concern before the war about the potential for air-to-ground friendly fire casualties, ground-to-ground friendly fire cases were more than twice as numerous—2.14:1—as air-to-ground incidents.)

Opting for "boots on the ground" for whatever reason can be a costly mistake, even in conflicts judged (usually wrongly) as "unsuitable" for air power, or when planners and decision-makers believe them to be strictly humanitarian in nature. For example, October 3, 1993, "Bloody Sunday," in Mogadishu cost the United States 18 dead and almost 100 wounded in close combat—the most costly and intense U.S. Army combat engagement since Vietnam. Tragically, this was a combat fought in the absence of dominant, air-delivered fire support because appropriate naval and Air Force forces had been withdrawn from Somalia even though, in retrospect, air could have made a significance difference. Though not perhaps fully appreciated, the Bosnian experience likewise offers a cautionary tale: NATO airmen undertook Operation Deliberate Force in 1995 and established the conditions under which a peace could be secured in the Balkans; they did so with the loss of a single aircraft and the imprisoning (and subsequent release) of its two-man crew. Prior to this, however, the United Nations had struggled with no great success for nearly four years to bring about a peace—and the UN ground presence suffered 1,690 casualties with 214 killed, of which 708 casualties and 80 killed were as a direct result of enemy action. So much for "risk free" peace keeping.

Fortunately, the appropriate use of modern aerospace power can minimize the risk of the close fight by changing engagement strategies from ones emphasizing close-combat to those emphasizing reach and remote fires. "Seizing and Holding" is less important than "Halting and Controlling," permitting an *effects-based* strategy rather than a strategy that, at root, echoes the attrition warfare of the past. Such an approach offers the potential for asymmetric advantage over opponents, and is consistent with the increasing diminution of the battlefield as the arbiter of victory in warfare.

An example of one such approach is the increasing reliance upon so-called “No-Fly Zones” (NFZs). NFZs offer what is in effect aerospace-based diplomacy and statecraft. The imposition of an NFZ gives an advanced nation the means to control an opponent at minimal risk to its own personnel and resources: there are minimal “boots on the ground” (except in neighboring countries who are presumably allies or otherwise coalition partners). As the stealth revolution was predicated on the unhinging of the basic premises behind the Warsaw Pact’s air defense system—namely the reliance upon early warning, search, and fire control radars and radar-dependent weapons such as missiles and fighters—NFZs may be said to negate a nation’s basic investment in a large standing army.

As Brig. Gen. David Deptula, the U.S. Air Force Commander of Operation Northern Watch, has noted:

> Large armies exist for the express purpose of taking and holding territories. Nations with territorial ambitions put great stock in large armies for this reason alone. “Boots on the Ground” are an aggressor's weapon of choice—they certainly were for Saddam Hussein. Air occupation does not seize and hold territory in the same way that land forces do. It stops an adversary from operating in a specific area without accruing any territory for the nation or nations actually carrying out the air occupation. Thus it is a “non-provocative” action that cannot easily be misconstrued as an “imperial” action, and that is one of the reasons air occupation is becoming the intervention option of choice at the cusp of the 21st century.

As NFZ operations indicate, overall, as aerospace capabilities have matured, the effects obtainable through aerospace action have dramatically increased, while casualties to surface forces have equally dramatically declined.

The Investment Dimension

This illuminates an important principle, however: To obtain the advantages of aerospace power requires constant and appropriate investment in high technology. That investment, historically, has improved system performance, reliability, and readiness, and has resulted in fewer losses of both systems and people. The results are often dramatic. For example, an examination of four American conflicts found interesting connections between research and development budget authorizations, increases in bomb accuracy, reductions in the number of aircraft required to guarantee destruction of a target, and reductions in U.S. Army casualties in battle:

	WW-2	*Korea*	*Vietnam*	*Gulf*
Ave. R&D Budget Authority (Billions, Constant '98 USD)	0.49	3.23	13.35	13.71
USAF Bomb Accuracy (CEP, ft.)	3,300	1,000	400	10
Aircraft Required to Destroy a 60 x 90 ft. Target	3,024	550	44	1

	WW-2	*Korea*	*Vietnam*	*Gulf*
U.S. Army Casualties per Day	0.0500	0.0400	0.0300	0.0016
As a % of Theater Strength	(1/20)	(1/25)	(1/33)	(1/625)

The advantages of aerospace power only come through strong national support, and, for all nations that employ forms of aerospace power, that continued support is critical, particularly in an unstable and fragmented world such as we all occupy today. The ever-evolving threats to employing military forces from new advanced weaponry is such that if such support flags or lags, nations run the risk of ceding control of the air to potential opponents in the twenty-first century and, as a consequence, risking as well their ability to prosecute successful joint and combined warfare. At a minimum, a nation to be considered a true aerospace nation should have the capabilities to undertake air superiority, air mobility, precision attack, reconnaissance, and the attendant host of related missions from combat search and rescue to robust and realistic training, all within a well-maintained, motivated, trained, and led service. Above all, a nation has to have the ability to ensure control of its airspace, for control of the air is essential to all joint warfare operations. Prudent investment, even for smaller nations, can have surprising payoffs, particularly in this era of coalition-building and coalition-participation, as we have seen from Africa to the Gulf and on to the Balkans.

In this process, of course, thorough and well-thought-out testing is key. Not adequately considering the role of the tester can lead to, at best, delays and cost escalation, and, at worst, program failure and, perhaps, human lives. Sadly, such has occurred frequently in both American military history and that of other nations. In this regard, we have to be particularly careful in an era appropriately demanding as much “off the shelf” procurement as possible that we recognize that the particular and special needs of military forces are not necessarily congruent with those of the civilian community. Such “off the shelf” systems require special consideration and examination by the test community to ensure that they meet the operational and safety needs of our military forces. Additionally, we must not confuse—as many nontechnologists do—“test failure” with “program failure” lest we risk embarking upon a fruitless tail-chase for perfect or near-perfect solutions. Had such a mindset existed in planners of an earlier era, some notably successful weapon systems now in use (particularly precision munitions and missiles) would never have had the opportunity to enter service. Arguably, such a mindset in the so-called “defense reform” movement of the middle-to-late 1980s came surprisingly close to derailing many of the weapon systems that performed so well in the Gulf War, notably stealth, attack helicopters, battlefield missile systems, space-based navigation systems, and others both large and small.

In Conclusion . . .

It has been the unhappy lot of the Western Alliance since 1989 to have to assume a far greater role in ensuring global peace and stability than could have been predicted as waves of German youths tore down the Berlin Wall and images of a new millennial age of peace, freedom, and prosperity loomed. Since that time, ugly conflicts in far-flung corners of the globe and ongoing national, religious, and ethnic disputes have tempered the optimism with which many greeted the collapse of Soviet totalitarianism. The world today increasingly appears like its predecessor, but with far less stability and predictability. If large-scale alliance system threats have disappeared, there has nevertheless been a proliferation of smaller threats, and the specter of some truly violent conflicts to come, possibly involving the use of weapons of mass destruction, including nuclear weapons. For this reason, the rise of aerospace power, unique to this century, can only be seen as most welcome. Its capabilities today are consistent with historical experience and offer the potential of unprecedented advantages for the United States and its allies as we all enter the twenty-first century. Ensuring that the nations of the Western Alliance retain robust joint service aerospace power capabilities is arguably the greatest acquisition, testing, and organizational challenge facing our national defense establishments today. For that reason, one of the most important functions any of us can undertake is to further the defense debate and dialogue by examining what air power—and now aerospace power—has and can offer to our mutual national security concerns. I hope that this presentation has stimulated some thought and discussion to that end, and I welcome your questions and comments.

Developing Missile Flight Controls: From Guide Sticks to Impulse Thrusters

Donald R. Baucom

The Origins of Flight Control Technology

From the first appearance of the military rocket in China during the thirteenth century, the effort to achieve stabilized, controlled flight was one of greatest challenges of rocketry. Primitive gunpowder rockets attained a limited degree of flight control by means of a stabilizing guide stick, a simple pole that was attached to the side of the powder tube.[1]

The guide stick remained the basic means of ensuring stable flight until the middle of the nineteenth century when Englishman William Hale eliminated the need for the cumbersome guide stick by developing a system of ports that imparted a stabilizing spin to the rocket.[2] In Hale's first spinning rocket of 1844, the rotation was produced by means of holes drilled into the base of the metal rocket just above the rocket's single thrust port. These four holes were lined up equidistantly around the circumference of the rocket's base and were drilled at angles so that a small amount of the rocket motor's expanding gases escaped through the holes in a pinwheel pattern, causing the rocket to spin. Later modifications would steadily improve the efficiency of Hale's initial method of spinning rockets.[3]

Until the first half of the twentieth century, rockets remained relatively small and simple. However, by the 1930s inventors and developers were experimenting with liquid rockets that increased steadily in size and complexity. These new designs brought with them demands for greater control forces to assure the stable flight of large, heavy liquid-fueled rockets.

Goddard and Flight Controls for Liquid-Fueled Rockets

Liquid-fueled rockets developed in the 1920s and 1930s were launched vertically. As a result, they posed special control problems during the critical period between lift-off and the time when the rocket achieved sufficient velocity for aerodynamic surfaces to develop control forces adequate to offset factors such as the effects of wind gusts and minor discrepancies in calculations of thrust vector and center of gravity.

The first person to address this problem was American rocketeer Robert H. Goddard,[4] who is most famous for developing and flying the first liquid-propellant rocket. This flight took place at Auburn, Massachusetts, on March 16, 1926.[5]

Goddard's most important work on flight controls came after 1930 when he moved his base from Massachusetts to a site near Roswell, New Mexico. He understood that at the point of lift-off, crosswinds striking large stabilizing fins could cause loss of control. He also recognized that anything protruding into the slipstream would produce drag and should therefore be eliminated if possible. Goddard's solution was to use small vanes so located at the base of the rocket as to extend into the rocket exhaust. When properly turned, these jet or blast vanes changed the vector of the thrust, thereby generating control forces. The turning of the vanes was controlled by a gyroscope that sensed changes in the flight angle of the rocket. Goddard successfully tested this control system in a flight on April 19, 1932, and received a patent for the system on September 27 of the same year.[6]

Jet vanes were not without shortcomings. Since they protrude into the exhaust stream, they reduce the efficiency of a rocket motor.[7] In Goddard's words, they produce "a large parasitic resistance . . . at very high speeds." Additionally, once an engine burns out, the vanes are no longer effective. [8]

To improve stability during powered flight and to provide control after burnout, Goddard experimented with a variety of configurations that combined different sets of air vanes and stabilizing fins. One design had a set of four air vanes that were flush with the rear fuselage surface until extended. These resembled the air brakes or speed boards employed on modern fighter aircraft. A number of these control schemes were flight-tested in March, April, and May of 1937.[9]

But Goddard was not totally satisfied with any of his approaches to flight control. Therefore, in the summer of 1937, he developed a new approach that combined the effects of air and jet vanes without their increased drag and decreased engine efficiency. This new control method comprised two components. First, "the chamber and tapered tailpiece were accordingly mounted so as to be movable about a point above the chamber, in two directions at right angles. Sidewise motion was arranged to take place by gyroscopic control, and return to axial alignment was made forcibly, as soon as the gyroscopic control ceased." This technique meant that the rocket motor could be used to generate control forces as soon as it was ignited, just as jet vanes did, but without any protrusion into the rocket exhaust. The second component of Goddard's new technique "consisted in having the rear section of the tapered tailpiece, enclosing the chamber, capable of being moved laterally, and of being returned to axial position, by gyroscopic control." This movement would generate aerodynamic control forces after the rocket reached a certain minimum speed and would continue to provide these forces after engine burnout.[10]

Goddard's development of this first gimbaling technique and his other achievements were impressive. However, they had little influence on the mainstream of rocket development. Like the Wright brothers before him, Goddard was very concerned about securing patent rights on all of his developments. (He was eventually granted a total of 214 patents.) As a result, he was extremely secretive about his work. He swore his technical assistants to silence and published little until his famous 1936 report to the Smithsonian Institution. By that time, German rocketeers who were well along in developing their own liquid-fueled rockets found virtually nothing helpful in Goddard's work. It was the Germans who would turn a technical curiosity into the practical device that facilitated space flight and a new form of strategic warfare.[11]

Refining Controls: The German V–2

One of the most important steps in the development of the liquid-fueled military rocket occurred in 1930 when Capt. (later Gen.) Walter Dornberger was assigned responsibility for Germany's highly secret military rocket program. He had served with heavy artillery units in World War I, which had been dominated by the big guns. The artillery had found its apotheosis in the great Paris gun that hurled twenty-two pound artillery shells into Paris from a distance exceeding seventy miles. It is hardly surprising, then, that Dornberger made the performance of the Paris gun the standard against which Germany's first liquid-fueled military rockets were to be measured. Dornberger told his team of rocket developers that their goal was to develop a rocket that would exceed the capabilities of the Paris gun while eliminating the "terrible weight" of the gun itself. This liquid-fueled rocket was "to be launched vertically, and to be programmed later into an elevation of 45 degrees. The rocket should carry a hundred times the weight of the explosives of the Parisian gun [i.e., 1,000 kg] . . . over twice the range."[12]

Another critical step came in the fall of 1932 when Dornberger hired Wernher von Braun, a brilliant young engineer. Soon, von Braun was joined by others, setting in motion a chain of events that led to the establishment of the Peenëmunde rocket team.[13] With von Braun as its leader, the team developed a series of rockets designated A–1 through A–5, the "A" standing for Aggregate.

The first of these rockets, the A–1 and A–2, were stabilized by means of a large gyroscope that was spun around the longitudinal axis of the rocket. When this system proved unreliable, the Germans set about designing a new guidance and control system for the next test series, the A–3.[14]

This new system consisted of a gyrostabilized platform equipped with accelerometers and servomotors that were connected by means of control rods to molybdenum-tungsten jet vanes. Guidance commands went to the servomotors that moved the rods, changing the position of the vanes, thereby producing the desired control forces. Additionally, the A–3 was stabilized by fins at its base.[15]

The design of the fins was of considerable significance. Indeed, one problem with earlier efforts to develop fin-stabilized rockets was inadequate knowledge of fin properties. Through the Technical Office of the Luftwaffe, von Braun was introduced to one of Germany's "supersonic wind tunnel groups," which was located at the Technical University at Aachen. Dr. Rudolf Hermann of this group "made the preliminary drag measurements that allowed a calculation of the performance of the rocket. He then worked on the fin form so that stability through the whole range from zero velocity to supersonic was assured."[16]

The first four A–3 launches ended abruptly with the rocket going out of control. Analysis of these flights pointed toward an inadequate control system as the prime cause of the failures. Because of the inherent stability of the A-3, the jet vanes generated insufficient forces to counteract the effects of cross-winds on the rocket.[17]

The Germans had expected to go directly from the A–3 to the A–4, which was to be the prototype of the V–2. However, the major deficiencies in the A–3's guidance and control system meant that another stage in development was necessary to assure that the A–4 would function properly. Therefore, the Germans decided to proceed through an intermediate development stage; since A–4 had already been selected as the designation for the V–2 prototype, the new development stage was designated A–5.[18]

Efforts to resolve the guidance and control problems included both a technical and a managerial component. Where management was concerned, the Germans decided to introduce competition into the development of the guidance system. Kreiselgeräte Limited, which had been the central developer of the guidance system to this point, would continue its efforts to solve the problems of the failed A–3 guidance system. At the same time, the Siemens Corporation was to begin work on a guidance and control system that would build on the hydraulic servomotor technology it had developed for use in autopilots. In this system, electrical signals were converted into variations in hydraulic pressures which in turn were used to move the vanes in the rocket's exhaust. A third contender in the guidance and control competition was the Askania instruments firm.[19]

By mid-1941, "repeated launches with the A–5 had shown that stable flights could be achieved" with all three guidance and control systems that the Germans had then developed. However, the extensive up-scaling that would be necessary to achieve a missile with the operational capabilities expected of the A–4 meant that the operational system would have to generate considerably larger control forces. Only the hydraulic approach used by Siemens seemed capable of providing the greater control forces that the A–4 would demand, and even its success was uncertain. At this point, an important mixer device was developed that allowed the guidance and control system to better "read" the conditions of a missile's flight and provide more accurate guidance commands.[20] The mixer proved to be a critical breakthrough that hastened the solution to scaling up the guidance and control system.

The final denouement of the process was the decision to speed the development of the A–4/V–2 guidance and control system by combining components from all three of the competing companies to produce a workable hybrid system. Included in this decision were judgments as to which companies could produce which components in the fastest, most efficient manner.[21]

At least two other important technical changes were made to the control system. The jet vanes were manufactured from graphite rather than the expensive metal alloy, thereby reducing the cost of these vanes by a factor of one hundred. Additionally, small rudders were added to the stabilizing aerodynamic fins of the missile. Both the jet vanes and the rudders were activated by hydraulic servomotors.[22]

The solution of the guidance and control problems as reflected in the success of the A–4 tests was the spectacular final act in the V–2 development program. In "five short years," wrote historian Michael Neufeld, the Germans had established the "foundations for a technological revolution in rocketry."[23]

Rocket Developments at the Outset of the Cold War

After World War II, the German rocket program became the fountainhead of missile programs for both the United States and the Soviet Union. In the case of the United States, Project Paperclip uprooted the central elements of the Peenëmunde program and transplanted them at Fort Bliss, Texas; White Sands, New Mexico; and Redstone, Alabama. Over one hundred of Germany's top rocket scientists, along with one hundred operating V–2 rockets, were shipped to the United States where they formed the core of America's nascent missile program. Indeed, the V–2 became the basic model for the first large missiles built in the United States.[24]

One U.S. derivative of the V–2 was the MX–774 missile developed by the Air Force and Consolidated-Vultee Aircraft Corporation (Convair). This rocket used gimbaling to control its flight, although the project manager, Karel J. Bossart, was apparently unaware that Goddard had flight-tested a gimbaling system in July 1937.[25] Bossart's attitude control system was a marked improvement over the jet vane system used in the V–2.

Another early U.S. missile to employ gimbaling was the Viking, which made its maiden flight on May 3, 1949. Viking also employed "small hydrogen peroxide thrust jets placed at various points around the rocket" to enhance the missile's stability during flight through the upper atmosphere.[26]

In the same year that Viking first flew, American A.E. Wetherbee, Jr., developed the concept for a new form of missile control. It entailed injecting a fluid, either inert or reactive, into a rocket motor's exhaust stream, thereby changing the flow of hot gases and producing control forces that arise as a result of such things as disruptions in the boundary-layer flow and the formation of shock waves. In the case of the injection of an interactive fluid, primary and secondary combustion interactions are also generated, producing additional control forces.[27] This method of control was used not only in ballistic missiles, but in America's first operational missile defense system as well.

Control Systems for Early Missile Defense Interceptors

While a principal concern in developing large ballistic missiles was stability of flight, a missile defense interceptor had to be not only stable in its boost phase, but capable of dramatic high "g" maneuvers during the terminal phase of flight when it must maneuver to close with its target. In the first three decades after World War II, the requirement for maneuverability was lessened by the use of nuclear warheads that were required to compensate for limitations in sensors and computers. However, after the mid-1970s as technology advanced and the United States moved from missiles with nuclear warheads to hit-to-kill interceptors that actually collide with their targets, maneuverability demands increased substantially.

The only national missile defense system the United States deployed was known as Safeguard, a layered system that employed two types of missiles, each of which intercepted attacking warheads in different bands of the atmosphere. Spartan, the larger and longer-ranged of the two, operated in the high-endoatmospheric battle space from seventy to one hundred kilometers above the earth. The smaller, faster Sprint intercepted leakers (attacking warheads missed by Spartan) after they had penetrated deeply into the atmosphere where atmospheric friction would strip away decoys and booster debris, making it relatively easy for Sprint to find its target warhead. Since the state of the art in sensors, guidance, and control was rather limited in the 1950s and 1960s when Sprint and Spartan were developed, both missiles were armed with nuclear warheads. What the use of nuclear warheads meant regarding accuracy requirements can be seen by looking at the first test in which a Nike-Zeus missile, forerunner of Spartan, "successfully" intercepted a dummy warhead over the Pacific in July 1962. At its closest approach to the target, Zeus was about two kilometers away, yet this was deemed close enough for Zeus' powerful warhead to be effective.[28]

Spartan was hot-launched at an 85-degree angle, with a launch rail providing stability as it exited its silo.[29] After launch, the missile flew without changes in trajectory until the first-stage motor burned out. During this portion of the flight, directional stability was maintained by means of airflow over fixed vanes on the first and second stages and over the locked, but movable, steering vanes on the third stage. After first-stage burnout and jettisoning, the second stage ignited, and the movable vanes on the third stage were used to steer the missile toward its target. After second-stage burnout, when the missile was essentially outside the atmosphere, the third-stage motor was fired to move the missile into its final intercept trajectory. At the same time, some gases from this motor were vented through nozzles in the trailing edges of the third-stage control vanes to generate additional control forces to supplement the aerodynamic forces generated by the flow of thin atmospheric air over the vanes. Finally, the third stage was spun for stability as it approached its target.[30]

In spite of its nuclear warhead, Sprint's mission of picking up leakers in the lower atmosphere meant that its control system had to be capable of producing extremely high g maneuvers. Its mission profile called for it to intercept incoming warheads at altitudes of between 5,000 and 100,000 feet within seconds of launch. A typical intercept might occur at an altitude of 40,000 feet and a range of 10 miles after only 10 seconds of flight.[31]

Unlike Spartan, Sprint was cold-launched, with the interceptor ejected from its silo by a gas-powered piston. Once out of the silo, its powerful rocket motors rammed the missile through the dense lower atmosphere causing its skin to glow incandescently due to atmospheric heating. During first-stage burn, control forces were generated by a thrust vector control (TVC) system that injected Freon into the motor's nozzle from four different points. (Freon was selected because of the experience gained with its use in the TVC systems of Minuteman and Polaris.) After booster separation, the second stage was guided by means of aerodynamic forces acting on small control vanes at the base of this stage.[32]

Even as the development of Spartan and Sprint was being completed, the Defense Department's Advanced Research Projects Agency (ARPA) was supporting several programs to improve the performance of missile defense interceptors. Two of these, HIBEX and UPSTAGE, focused on Sprint. Their purpose was to develop an improved interceptor for hard-point defenses that would protect targets like missile silos.[33]

HIBEX, which stood for High-g Boost Experiment, was a two-year research program (1964–1966) sponsored by ARPA's Project Defender. It aimed to develop an improved first stage for Sprint, producing a booster with very high performance parameters. After burning for only 1.24 seconds, the 500,000-pound-thrust HIBEX booster imparted a velocity of 8,408 feet per second to the HIBEX vehicle. The g forces associated with such a flight were extremely high: an axial acceleration of 362 g and approximately 60 g of lateral acceleration. In its final flights, the missile achieved maneuvers of 75 degrees pitch change and azimuth changes of 45 degrees.[34]

As in the case of the Sprint first stage, the principal means of control in HIBEX was the injection of Freon gas into the exhaust of the booster. However, in later flights, experiments with other control techniques were performed. The TVC system of HIBEX consisted of four valves spaced at 90 degrees around the nozzle of the motor; each valve was capable of injecting a total of 194 pounds of Freon per second at 1,400 psi. Each valve fed three nozzles. HIBEX carried a maximum of 98 pounds of Freon, but only 78 pounds were usable. The Freon was fed by means of a blow-down system that used compressed nitrogen as its source of pressure. This system was designed to provide 2.5 degrees maximum thrust vector deflection which amounted to 2.5 percent of motor impulse with a maximum response time of 20 milliseconds. This thrust was the equivalent to a "side force" of 15,000 pounds in less than 0.05 second.[35]

A total of seven flights were carried out in the HIBEX program. The last two (D–3 on December 2, 1965, and D–4 on January 5, 1966) included reaction-control experiments,[36] which can be understood through an analogy with conventional aerodynamic controls. "As fins attain their control-force generation by deflecting streamlines over the fin surface, thereby achieving a favorable interaction with the passing atmosphere, so reaction controls obtain their favorable interaction with the atmosphere by deflecting the passing flow over the vehicle body outward from the body." In other words,

> reaction controls are those controls which attain this favorable interaction with the atmosphere by utilization of some phenomenon other than the deflection of the surface. This streamline deflection can be attained by heating the air by burning fuel in it, by injecting a jet of gas or liquid into the passing air stream and creating a shock and/or separation region by the issuing jet, or perhaps by heating the vehicle surface and deflecting the air as a result of the heating, or alternatively, by seeding the passing air stream with an ionized material and deflecting the total stream electrostatically or magnetically.[37]
>
> In the reaction control tests of flights D–3 and D–4, a pyrophoric substance, triethylaluminum (known as TEA), was fed into the stream by an injector fifteen inches from the base of the second stage at 1.5 seconds into the flight. The results from these two experiments were disappointing. In D–3, the second stage did not separate; and although the external burning seemed to operate as planned, test results were inconclusive. In the case of D–4, the effects of the external burning were only about 30 percent of the predicted value.[38]

In the 1965–1968 period, the external burning experiments of HIBEX were extended in the PRESTAGE program, which explored external burning in a hypersonic flow and examined the problems associated with controlling the lateral and axial thrust that resulted from the burning. PRESTAGE also entailed experiments with "'disposable' vanes" as well as lateral jets for thrust vector control.[39]

External burning, along with jet interaction, was explored further in UPSTAGE (Upper STage Acceleration and Guidance Experiment), an ARPA project begun in 1968 to develop a second stage to match first-stage developments stemming from HIBEX. UPSTAGE was to be extremely agile so it could be used against a maneuvering reentry vehicle. Five UPSTAGE flights were completed. In these demonstrations, the vehicle developed over 300 g of lateral acceleration and "provided ample demonstration of the effectiveness of both E[xternal]B[urning] and J[et]I[nteraction]." External burning developed control forces of more than 33,000 pounds and specific impulses that exceeded 610 seconds. Two experiments with jet interaction produced specific impulses of 649 and 565 seconds.[40]

As impressive as were the results of programs like HIBEX and UPSTAGE, they did not solve the basic shortcoming of Safeguard. As already noted, both Spartan and Sprint had to be armed with nuclear warheads to have a reasonably high probability of destroying their targets. Yet the detonation of a nuclear warhead essentially blinded Safeguard's radar systems, disrupting the defender's ability to control the defensive battle. Safeguard was further hampered by the ABM Treaty of 1972 and its 1974 Protocol. The one hundred interceptors allowed under these agreements could be easily overwhelmed by Soviet strategic rocket forces. For these reasons, Congress closed the Grand Forks, North Dakota, Safeguard site in early 1976, about three months after it became operational.[41]

With the closing of Grand Forks, the U.S. Army focused its missile defense research on eliminating the technical deficiencies exhibited by Safeguard. One promising possibility was the exploitation of hit-to-kill technology, which had been under development for a decade and a half by the time Safeguard was closed.[42]

Origins of Hit-to-Kill Technology

Discussions of hit-to-kill interceptors date back to ARPA's Project Defender which was started soon after ARPA was established in 1958. In a July 1960 address to a gathering of representatives of the missile defense community, Dr. Harold N. Beveridge noted that the "quest for a cheap kill in a terminal defense system" had led Project Defender participants to conclude that hit-to-kill systems were feasible:

> Computer simulation runs on several types of interceptors weighing about 50 lbs., and using IR homing have resulted in miss distances of one or two feet. This certainly indicates hyper velocity impact kill could be employed. Incidentally, a nose cone traveling at ICBM velocities in collision with one pound of material releas-

> es the energy equivalent of 6 pounds of TNT. In a word, the kinetic energy at that velocity exceeds the chemical energy available at that mass.[43]

Within about two years of Beveridge's remarks, LTV Aerospace Corporation conceived the Homing Interceptor–Terminal (HIT). HIT was to be "a small and lightweight, spin stabilized, optically guided interceptor that achieves hypervelocity direct impact kill of reentry vehicles in the exoatmosphere."[44] In spite of its small size (about fifteen pounds), it was to have "all the features of a large conventional interceptor." Furthermore, HIT's small size meant that several interceptors could be mounted on a single booster, offsetting to some extent the advantage of MIRVed ICBMs. Finally, HIT was to have a fundamentally simple design that involved no moving parts.[45]

HIT's control forces were produced by tubular, solid-propellant impulse motors, each with a nozzle located midway along its tube. A number of these motors were assembled into a tube of tubes, with the motor nozzles pointing outward. In one version, sixty-four motors were joined to form a motor assembly that also served as the main structure of the interceptor's body. Each of these motors provided a single thrust pulse yielding a ΔV (velocity change) of about 20 feet per second for a total system ΔV of approximately 1,265 feet per second. Since the HIT vehicle was spin-stabilized, directional changes were accomplished by firing a motor when it was in the proper position to provide the required thrust vector.[46]

Around 1975, the Vought Corporation began to apply HIT technology to the Miniature System Project that was sponsored by the U.S. Air Force Space and Missile System Organization. This project called for a HIT vehicle similar to the one described above to collide with an orbiting satellite after being launched either by a ground-based or air-based rocket booster, depending on the orbit of the satellite being attacked.[47] A major milestone in the HIT technology program came on September 13, 1985, when an Air Force antisatellite (ASAT) system launched by an F–15 fighter destroyed an Air Force satellite designated P78–1, known primarily for its principal payload, a gamma ray spectrometer belonging to ARPA. The kill vehicle of this ASAT system was the miniature homing vehicle, which had emerged from the Miniature System Project and was virtually identical to the HIT vehicles developed by LTV and tested in that company's 1976 integrated system tests.[48]

Missile Interceptor Control: The Case of ERINT

In January 1983, a little over two years before the successful ASAT test, the Army awarded Vought a $70 million contract to develop the small radar-homing intercept technology (SRHIT) interceptor, which was to destroy targeted missiles by crashing into them.[49]

SRHIT was to incorporate technologies developed over the previous decade by the Air Force and the Advanced Technology Center of the Army's Ballistic Defense Command. The Army's contributions to SRHIT included advances in on-board sensors and computers, as well as a system for flight control that was similar to the system developed in the HIT program. Moreover, the laser-gyro inertial reference system that had been pioneered in Vought's HIT and Miniature Homing Vehicle programs was incorporated into SRHIT.[50]

The flight vector of SRHIT was to be controlled by one hundred small rocket thrusters that formed a belt around the missile, an arrangement reminiscent of the thruster configuration of the HIT vehicle. Also like HIT, SRHIT was to rotate in flight, with SRHIT's rotation rate being one hundred revolutions per minute.[51]

This rotation was not so much to stabilize the missile as to assure that the control system would operate properly throughout SRHIT's flight. Each of the thrusters could fire only once. Therefore, if the missile did not rotate, firing the thrusters in a given sector of the thruster belt would create a dead section, making it impossible to accomplish more than a single turn in a given direction. Rotation ensured that a live thruster would always be available in all firing positions until all thrusters in the belt had been fired. The number of thrusters would be based on operational analysis so that in theory the intercept mission of an SRHIT would never require the firing of more than one hundred thrusters.

A total of nine flight tests were planned for the SRHIT program. These were to demonstrate "progressively greater combinations of the total set of desired flight vehicle performance characteristics."[52] However, about the time of the third test, the name of the program was changed from SRHIT to FLAGE, for Flexible Lightweight Agile Guided Experiment.[53] FLAGE inherited what was essentially the test schedule for the SRHIT program so that tests four and five in the SRHIT program became tests one and two for FLAGE.[54]

In its first two tests, FLAGE missiles were to demonstrate the "ability of the rocket motors to produce adequate control authority to guide the missile, and test the radar's ability to home on a stationary target." This target was an aluminum sphere, forty-four inches in diameter, suspended beneath a tethered balloon, 12,000 feet above the ground.[55] On April 20, 1986, a FLAGE missile destroyed one of these tethered targets.[56]

In its third test on June 27, 1986, the interceptor destroyed a target missile that was traveling at five times the speed of sound.[57] This test confirmed "that FLAGE's guidance and control technologies could provide the accuracy needed for direct impact of hypersonic targets with simple radar signatures."[58] The test had a further significance in that it was the first demonstration of a hit-to-kill intercept of a tactical ballistic missile.[59]

The fourth test came on May 21, 1987, when FLAGE destroyed a short-range surface-to-surface Lance missile at an altitude of 16,000 feet. This was a more realistic test, as the Lance missile more nearly replicated the radar signature and performance of a tactical ballistic missile.[60]

In 1987, the work started under SRHIT and FLAGE was folded into the ERINT (Extended Range Interceptor) program, which began as an $80 million, three-year contract between the Army's Strategic Defense Command and LTV Aerospace. Under this contract, LTV was to extend the technology developed in the FLAGE program so that intercepts could be completed "at more realistic intercept altitudes, velocities and mission timeliness." FLAGE had been designed to intercept targets with speeds of 3,000 feet per second at an altitude of about 2.5 miles. The ERINT interceptor was to be capable of intercepting targets moving at 11,000 feet per second at altitudes as high as 9 miles. Like FLAGE before it, ERINT was to explore the efficacy of hit-to-kill technology as applied to the theater missile defense mission.[61]

The greater performance demanded of ERINT meant that the new missile would have to differ substantially from FLAGE. At the outset of the SRHIT program, the SRHIT/FLAGE missile was to have been 9 feet long and 9 inches in diameter; as tested, it was 12 feet long. ERINT was to be 15 feet long and 10 inches in diameter. In addition to its greater size, ERINT was also fitted with a lethality enhancer, a device consisting of "a ring of twenty-four dense tungsten pellets that fire out from the missile in a disk pattern." The pattern of these pellets was to extend "a specific radius from the interceptor" that was equivalent to the "miss distance" that might be caused by a maneuvering target.[62]

ERINT's control system was also different. Throughout most of its flight, ERINT would be guided by "steerable fins." During endgame (the final seconds of the flight before collision with the target), directional control would be provided by 180 thrusters in a ring around the missile's body near its nose.[63] Like FLAGE, ERINT rotated as it approached its target, firing its thrusters as necessary. Since the interceptor would be moving at a very high velocity during endgame, each thruster pulse would produce very large aerodynamic control forces by moving the nose of the missile relative to the slipstream.[64]

ERINT's first two flights verified the soundness of the missile's structure and propulsion system and demonstrated the operability of the onboard radar and lethality enhancer. A third flight in August 1992 tested the missile's control system and verified its inertial flight performance. After failing to intercept its target in a June 1993 test, ERINT then successfully intercepted targets in two other tests, one on November 30, 1993, and another on February 15, 1994.[65]

Four days before the second test, the Army System Acquisition Review Council announced that ERINT would be the missile incorporated into the Patriot system under the PAC–3 upgrade program.[66] This decision marked a milestone in missile defense history, for it meant that ERINT would become the world's first operational hit-to-kill interceptor when it entered service around the year 2000.

Conclusion

Over the last seven hundred years, missile control technology has evolved from the simple guide stick designed to make a rocket fly a somewhat predictable course to the sophisticated attitude control system that allows ERINT to hit another missile traveling at two miles per second. During the last fifty to seventy-five years of this period, the rate of development has accelerated dramatically. It took seven centuries for rocketeers to produce the A–4/V–2, yet within fifteen years of the first missile attack on London, both the United States and the Soviet Union had deployed operational missiles that could deliver nuclear weapons over intercontinental ranges. Why this acceleration in the pace of development?

Prior to our own century, the development rate was constrained by limited theoretical knowledge and/or a restricted technology base. But as we entered the twentieth century, scientists and engineers gained increasing knowledge of complex phenomena through the application of sophisticated technology like supersonic wind tunnels, high-speed cameras, and electronic instrumentation. To this expanding knowledge base was added advanced techniques for manufacturing complicated devices and for producing materials tailored to withstand various forms of stress. The power of this mix increased further with the advent of state-funded and -guided research and development, which placed at the disposal of developmental groups the vast resources that modern, bureaucratic governments could mobilize. The result of this process has been optimistically referred to as invention on demand. We see this transformation illustrated in the development of liquid-fueled rockets.

Robert Goddard's operating mode contrasts sharply with that of Wernher von Braun's Peenëmunde group. Goddard represents the old approach used by Thomas Edison and the Wright brothers. Here, the lone entrepreneur-inventor gathered around him a small dedicated team of technicians and used limited private funding to support his work. Furthermore, since one of his major concerns was securing patent rights that would allow him to reap the profits of his inventions, the entrepreneur-inventor was loathe to seek help from others who might gain a basis for challenging future patents if they became involved in the work.[67]

By the time Goddard finished his work, further advances in rocketry had become dependent upon costly and sophisticated techniques and increasingly esoteric theoretical knowledge. In Goddard's work we see examples of careful, detailed work in many if all not of the multiple fields of technology upon which ballistic missiles are based. Nevertheless, Goddard had pushed rocketry as far as it could go under the coaxing of individual genius.

Von Braun, on the other hand, was recruited by Dornberger to head up a research program that was organized by the German Army. As the project built momentum, more and more resources were placed at von Braun's disposal. He was given sufficient funds to purchase the Peenëmunde site and establish there a lavishly equipped test facility. Moreover, he had at his disposal the German university structure and government laboratory system to assist in the solution of difficult problems such as the proper design for stabilizing fins. With the establishment of the German team at Peenëmunde, we see the birth of a future that would be dominated by command technology.[68] Peenëmunde foreshadowed the U.S. and Soviet missile programs of the Cold War.

When Robert Goddard died in August 1945, a developmental tradition died with him. But like Moses thirty-three hundred years earlier, he was allowed to glimpse the promised land he would never enter. In March 1945, he was invited to examine a captured V–2 rocket. One of his colleagues later reported that Goddard never got over what he saw. "He felt the Germans had copied his work and that he could have produced a bigger, better, and less expensive rocket, if only the United States had accepted the long-range rocket."[69] This melancholy episode serves to emphasize the point that from World War II the driving force in rocketry had become state-sponsored research and development.

Notes

1. For discussions of early rocketry, see Wernher von Braun and Frederick I. Ordway III, *The Rockets' Red Glare* (Garden City, N.Y.: Anchor Press/ Doubleday, 1976); Fang-Toh Sun, "Early Rocket Weapons in China," in Tom D. Crouch and Alex M. Spencer, eds., *History of Rocketry and Astronautics,* Proceedings of the Eighteenth and Nineteenth History Symposia of the International Academy of Astronautics, Lausanne, Switzerland (1984) and Stockholm, Sweden (1985), Vol. 14, American Astronautical Society (AAS) History Series, R. Cargill Hall, Series Editor (San Diego, Calif.: AAS Publications Office, 1993), pp. 3–15; Frank Winter, *The First Golden Age of Rocketry* (Washington, D.C.: Smithsonian Institution Press, 1990).

2. Winter, *Golden Age*, pp. 179, 182, 193.

3. *Ibid.,* pp. 194, 196–197.

4. For biographical information on Goddard, see Frank H. Winter, "Goddard: A New Perspective of the Man and His Achievements," *Space Times*, Mar–Apr 1997, pp. 4–9; J.D. Hunley, "The Enigma of Robert H. Goddard," *Technology and Culture*, Apr 1995, pp. 327–351.

5. Esther C. Goddard, "Introduction," pp. xi–xviii, in Robert H. Goddard, *The Papers of Robert H. Goddard*, ed. by Esther C. Goddard and G. Edward Pendray (New York: McGraw-Hill Book Co., 1970), Vol. I: 1898–1924. See p. xii.

6. Robert H. Goddard, "Liquid-Propellant Rocket Development," Mar 16, 1936, Report to The Daniel and Florence Guggenheim Foundation, in *Papers of Goddard*, Vol. II: 1925–1937, pp. 974–978. See also *Papers of Goddard*, Vol. II, pp. 822, 857. Apparently, Goddard did not make a specific entry in his diary about the April 19, 1932, flight, although p. 822 shows several pictures of the rocket fired that day. See also Michael J. Neufeld, *The Rocket and the Reich: Peenemünde and the Coming of the Ballistic Missile Era* (New York: The Free Press, 1995), p. 6. Here, Neufeld credits Goddard with being

the first to use vanes for flight control of a rocket. Winter, "Goddard," p. 9, also credits Goddard for being the first to use these vanes. For general information about Goddard, see von Braun and Ordway, *The Rockets' Red Glare*, pp. 126–127.

7. Jacob Neufeld, *The Development of Ballistic Missiles in the United States Air Force, 1945–1960* (Washington, D.C.: United States Air Force Office of Air Force History, 1990), p. 47, states that the jet vanes reduced the thrust of a rocket engine by as much as 17 percent.

8. *Papers of Goddard*, Vol. III: 1938–1945, pp. 1109, 1110, 1117.

9. *Ibid.*, pp. 1113–1116.

10. *Ibid.*, pp. 1110, 1117–1118.

11. Hunley, "The Enigma of Robert H. Goddard," p. 332; Winter, "Goddard," pp. 4, 9; M.J. Neufeld, *The Rocket and the Reich*, pp. 7, 53. Neufeld makes the point that the Germans probably did not have substantial information about Goddard's work until 1936. By this time, the Germans had surpassed Goddard. Speaking of Goddard's 1936 report to the Guggenheim Foundation, Neufeld wrote: "Nothing in the report would have shaken the [German] Ordnance group's confidence in its lead, nor did they glean any significant new technological concepts from Goddard." (p. 53) For information on the interest of the Wright Brothers in patent rights and their own tendency to keep the results of their work to themselves, see Tom D. Crouch, *The Bishop's Boys: A Life of Wilbur and Orville Wright* (New York: Norton, 1989), p. 231. Edison's biographer, Matthew Josephson, pointed out that after years of bitter patent litigation, Edison "became fairly secretive." Matthew Josephson, *Edison: A Biography* (Norwalk, Conn.: Easton, 1959), p. 390.

12. M.J. Neufeld, *The Rocket and the Reich*, pp. 51–52. On p. 52, Neufeld wrote: "Thus, in a fundamental sense the A–4 was another Paris Gun."

13. Frank H. Winter, *Rockets into Space* (Cambridge, Mass.: Harvard University Press, 1990), p. 35.

14. M.J. Neufeld, *The Rocket and the Reich*, pp. 35–38. Two A–2 rockets were successfully flown, but both flights were ended when wind gusts against the rockets caused their gyrostabilizers to precess and tip them over in flight.

15. *Ibid.,* pp. 66–67. These fins, of course, acted like feathers on an arrow. When the yaw and pitch of the missile changed, the fins produced counteracting aerodynamic forces that tended to return the missile to a stable position, with its nose pointing into the airstream. The Germans' used the term "arrow stability" to refer to the longitudinal stability of their rockets.

16. *Ibid.,* pp. 67–68.

17. *Ibid.,* pp. 69–71. The Sg 33 stable platform that was the heart of the A–3's guidance system was not designed to allow rotation around the missile's longitudinal axis. If the roll rate exceeded 6 degrees per second, it would cause the platform to tumble. Since the rocket was expected to pitch over at the top of its trajectory, causing the platform to tumble, the tumbling of the platform was to trigger the deployment of a parachute to bring the rocket down. In test flights, the parachute deployed early in the flight. This indicated that the platform had tumbled and could no longer properly sense the flight path of the rocket.

18. *Ibid.,* pp. 71, 74, 88–89. The A–5 looked like a scaled-down V–2. The body of the A–5, which became the model for the aerodynamic shape of the A–4, was slightly fatter than that of the A–3. Although the Germans faced a considerable challenge in going from the 3,000-pound thrust A–3 engine to the 55,000-pound thrust engine required if the V–2 were to meet its operational requirements, power plant development was not a major objective in the A–5 program, since the A–5 used the same engine as the A–3. See also photograph SI Neg. No. 76–15523 and its caption in the photograph section between pp. 82–83.

19. M.J. Neufeld, *The Rocket and the Reich*, pp. 94–99.

20. *Ibid.,* pp. 105–106.

21. *Ibid.,* pp. 99, 105–106, 108.

22. G. Harry Stine, *ICBM: The Making of the Weapon That Changed the World* (New York: Orion, 1991), p. 56. M.J. Neufeld, *The Rocket and the Reich*, p. 108, refers to "hydraulic vane servomotors."

23. M.J. Neufeld, *The Rocket and the Reich*, p. 108.

24. Winter, *Rockets into Space*, p. 52.

25. J. Neufeld, *Development of Ballistic Missiles*, pp. 36–37, 44–50, calls attention to the importance of Convair's MX–774 as the forerunner of America's first ICBM, the Atlas missile. Neufeld notes on pp. 36 and 45 that the point of departure for MX–774 was the German V–2 upon which its design was based. According to Stine, *ICBM*, pp. 143–146, although the Air Force canceled the MX–774 contract on July 1, 1947, Consolidated-Vultee continued the work, building and flying three missiles between July and December 1948. Hi-Roc (formal designation RTV–A–2) was the nickname of the missile that emerged from project MX–774. While Stine (p. 143) notes that Hi-Roc was the first American-designed rocket, he also states that it "used the basic configuration of the V–2" and even looked like a "baby V–2." Stein also noted that Bossart, Hi-Roc's designer, used gimbaling as the missile's control mechanism and that the work of Bossart and his team led eventually to the stage-and-a-half design of the Atlas missile.

26. Winter, *Rockets into Space*, pp. 66–67. Stine, *ICBM*, pp. 143–146, claims that gimbaling was pioneered in Hermes, Hi-Roc, and Viking. Dr. Goddard consulted at least briefly with General Electric on Project Hermes. However, General Electric canceled this relationship with Goddard, apparently because of Goddard's patent arrangements with Curtiss-Wright, which controlled the rights to a number of Goddard's patents. Nevertheless, Goddard had talked with GE about the development of rocket motors and may well have discussed the use of gimbaling as a form of flight control. For Goddard's contacts with GE, see *Papers of Goddard*, Vol. III, pp. 1580, 1588, 1590. For more information on Goddard's relationship with Curtiss-Wright, see *Papers of Goddard*, Vol. III, pp. 1472–1475, 1477.

27. George Sutton, *Rocket Propulsion Elements: An Introduction to the Engineering of Rockets* (New York: John Wiley & Sons, 1986), pp. 336–337.

28. Bell Laboratories, *ABM Research and Development at Bell Laboratories: Project History, 1975,* study completed for the U.S. Army Ballistic Missile Defense Systems Command under Contract No. DAHC60–71–C–0005, p. I-26. This test was classified as a partial success because the Zeus lost hydraulic power during the last ten seconds of its flight. Presumably, had the hydraulic system not failed, the interceptor would have come closer to its target.

29. Bell Laboratories, *ABM Research and Development at Bell Laboratories*, p. 10-6. Mr. Jack W. Kalish, a veteran of missile defense work, confirmed that the guide rail stabilized Spartan as it exited the silo. This confirmation came in a March 31, 1997, telephone conversation, between Mr. Kalish and the author.

30. Bell Laboratories, *ABM Research and Development at Bell Laboratories*, pp. 10-3–10-4. In the original Zeus design, the aerodynamic control fins were to have been located at the base of the second stage of the missile. A separate "jetavator" system was to be installed in the third stage. Developers of the missile decided to combine these two control systems in a set of fins that included jet nozzles for missile control outside the dense region of the atmosphere where aerodynamic control was possible. This allowed a reduction from two control systems to one and made possible the placement of all electronic controls in the nose of the missile. During early flight tests, the Zeus missile failed catastrophically, shortly after the missile reached its peak velocity. Ground cameras seemed to show a fire developing on the third stage, just before the failures. This made engineers suspect hydraulic failure as the source of difficulty. Not until pieces of a failed Zeus were recovered and analyzed was it found that the problem was in fact in the design of the control fins. A tiny gap between the third-stage fins and the missile's body allowed heat to build up on the steel control rods going to the fins with the result that the fins were cut

from the missile by excessive heating. A redesign of the fins eliminated this problem. (p. I-22)

31. Bell Laboratories, *ABM Research and Development at Bell Laboratories*, p. 2-9.

32. *Ibid.,* pp. 2-8, 2-9, 9-15, 9-16. The information about the use of the Skybolt pump is found on p. 9-16, while the information about Freon is from p. 9-15. In his March 31, 1997, conversation with the author, Jack Kalish pointed out that the conical shape of the Sprint missile itself was a stabilizing force during the missile's flight.

33. Richard H. van Atta, Sidney Reed, Seymour J. Deitchman, *DARPA Technical Accomplishments: An Historical Review of Selected DARPA Projects*, Institute for Defense Analysis Paper P–2429, Apr 1991, Vol. II, pp. 3-1–3-3.

34. Van Atta *et al., DARPA Technical Accomplishments*, Vol. II, pp. 3-6–3-8; Albert M. Jacobs *et al.,* "Interceptor Propulsion Technology," *Journal of Defense Research*, Series A: Strategic Warfare, Vol. 2A, No. 2, Summer 1970, p. 188, gives the dates of the HIBEX program as 1964–1966. According to van Atta (p. 3-8), a symposium on HIBEX was held in 1966 to review the results of the program. Several articles from this symposium provided the basic content for Vol. 2A, No. 2, Summer 1970, of the *Journal of Defense Research*.

35. Van Atta *et al., DARPA Technical Accomplishments*, Vol. II, p. 3-6; Boeing Company, *HIBEX Final Technical Report*, D2–99600–1, Mar 5, 1966, pp. 109, 119–121.

36. Boeing, *HIBEX*, p. 23

37. D.B. Harmon, Jr., "Reaction Controls for Interceptor Missiles," *Journal of Defense Research*, Series A: Strategic Warfare, Vol. 2A, No. 2, Summer 1970, pp. 231–232.

38. Boeing, *HIBEX*, pp. 37, 256–258.

39. Van Atta *et al., DARPA Technical Accomplishments*, Vol. II, p. 3-9.

40. *Ibid.,* Vol. II, pp. 3-1, 3-9; Riverside Research Institute (RRI), *Ballistic Missile Defense Research Tasks and Studies for the Period 10 December 1971 to 30 November 1972: Final Report F/186–3–16* , Contract No. DAHC60–71–C–0042, Jan 10, 1973, pp. 2–10, 22. The UPSTAGE jet maneuvering control technology was incorporated into SDI's HEDI missile (van Atta *et al.,* p. 3-1). RRI (p. 6) explains that external burning "consists of a combustion process that takes place upon the surface of a vehicle immediately subsequent to the addition of a pyrophoric fuel to the boundary layer. . . . Specifically, EB occurs when a fuel burning in air results in a transfer of thermal energy to the air flowing along the vehicle surface. When the air is thus heated, its volume increases and the streamlines are deflected. This deflection of the streamlines is accompanied by a change in the momentum of the air stream, and the force causing the change is transmitted to the vehicle surface in the form of varying surface pressures. As a consequence, the EB control technique makes possible the attainment of an aerodynamically clean vehicle design. As an added virtue, ultra fast control system responses are achieved for a low control subsystem weight investment." Both of these results—low mass of the control system and fast reaction time—are critical for light and agile interceptors. RRI (p. 8) notes that jet interaction is also a "fast-response control concept." In this control method, "a reaction jet exhausts into the flow field surrounding the vehicle, . . . The jet flow can be produced from a broad spectrum of possible system designs which include warm- or hot-gas solid propellant gas generators, and liquid bipropellant or monopropellant gas generators. The jet thus produced, which deflects the free-stream flow, creates a detached shock wave. A localized high-pressure area on the vehicle surface upstream of the reaction jet results. This high pressure, in turn, produces a control force on the vehicle surface. In addition to this in viscid interaction, there is a viscid interaction in which normal force is increased by the occurrence of boundary layer separation upstream of the shock wave. Both the viscid and in viscid terms provide control force increments which add to the momentum of the jet."

41. For information on the closing of Safeguard, see Donald R. Baucom, *Origins of SDI: 1944–1983* (Lawrence: University Press of Kansas, 1992), pp. 89–97.

42. R.A. Mail, R.A. Nordsieck, and J.W. Blum, *HIT System Study: Final Report*, General Research Corporation CR–12–144, May 1973, p. 1.

43. Harold N. Beveridge, "Defender Introduction," in Advanced Research Projects Agency, *A Review of Project Defender for the Director of Defense Research and Engineering, 25–29 July 1960,* pp. 17–18.

44. Missiles and Space Division, LTV Aerospace Corporation, *HIT Technology Program: Final Report*, Rprt No. 00.1372, Vol. I: *Executive Summary,* Dec 3, 1970, p. 1.

45. Vought Corporation, *Hit-to-Kill Homer Ground Test (HIT Phase II)*, Rprt No. 3–371–3R–Y–70024, sponsored by the U.S. Army Ballistic Missile Defense Advanced Technology Center under Contract No. DAHC60–71–C–0072, Feb 1977, p. 2.

46. Missiles and Space Division, LTV Aerospace Corporation, *HIT Technology Program :Final Report*, Vol. I, pp. 2, 17–18.

47. Vought Corporation, *Miniature System Project (Restructured Program)*, Mar 1979, pp. I, I-1–I-2, and sections III and IV. For a discussion of the application of the Vought vehicle to the ASAT program, see Craig Covault, "Antisatellite Weapon Design Advances," *Aviation Week*, Jun 16, 1980, pp. 243–245, 247. B. Shratter, J. Outenreath, and P. Sparrow, "HIT-to-Kill Vehicle Technology," *Journal of Defense Research*, Vol. 18, No. 4, Winter 1986, p. 676, state that after 1977 the HIT program became the basis for the Air Force ASAT program.

48. Vought Corporation, *Miniature System Project*, pp. iii-2, iv-1; Covault, "Antisatellite Weapon Design Advances," pp. 243–245, 247; "Defense Dept. Plans Next Test Firing of Air-Launched ASAT System," *Aviation Week*, Sep 23, 1985, pp. 20–21; David J. Lynch, "ASAT Hits Its Target in Space," *Defense Week*, Sep 17, 1985, p. 2.

49. "Army to Flight Test Nonnuclear ABM," *Aviation Week*, Jan 24, 1983, p. 30.

50. *Ibid.,* pp. 30–31. Covault, "Antisatellite Weapon Design Advances," p. 245, states that the use of the laser–gyro inertial system had been pioneered in Vought's HIT and Miniature Homing Vehicle programs.

51. "Army to Flight Test Nonnuclear ABM," *Aviation Week*, Jan 24, 1983, p. 31. HIT concepts called for various rates of spin. Two that I have seen are 20 and 50 revolutions per second.

52. "Public Affairs Plan for Flight Experiments of the Small Radar Homing Intercept Technology (SRHIT) Program," Mar 8, 1984, pp. 1–2; attachment 1, News Release 84–11–43, n.d.; and attachment 2, "Questions and Answers: SRHIT Flight 3."

53. I found no clear explanation of this name change. Ruth Currie-McDaniel and Claus R. Martel, *The U.S. Army Strategic Defense Command: Its History and Role in the Strategic Defense Initiative* (Huntsville, Ala.: Historical Office, U.S. Army Strategic Defense Command, 1989; 3d ed.), p. 51, simply state that the name SRHIT was changed to FLAGE. Dr. James Walker, U.S. Army Space and Strategic Defense Command Historian stated that although he could find no specific documentation on this name change, his records indicated that the change occurred between January 26, 1986, and May 16, 1986 (telephone conversation, Dr. James Walker and Dr. Donald R. Baucom, Jul 24, 1995). Dr. James Carlson, who was the director of the Army's Advanced Technology Center in the 1970s, stated that he did not know the exact reason for changing the name of SRHIT, but he did know that the acronym was constantly being misinterpreted to mean "short-range homing interceptor technology." Because of this, decision-makers in the Pentagon tended to see SRHIT as an insignificant program because the interceptor's "legs" (range) would be too short to permit an intercept at the minimum range for an effective defense. (Discussion, Dr. James Carlson and Dr. Donald R. Baucom, Jul 25, 1995.)

54. *N.B.*: I have found one indication of a possible difference between the SRHIT and FLAGE vehicles. U.S. Army Strategic Defense Command, Public Affairs Office, FLAGE Fact Sheet, Apr 1991, and Office of the Assistant Secretary of Defense (Public Affairs), "SDI-Related Test Intercepts Tactical Missile," News Release 268–87, May 22, 1987, state that FLAGE changed direction by selectively firing combinations of the 216 small rocket engines that girdled the missile just behind its radar dome. These rockets were

about the size of shotgun shells. As noted above, "Army to Flight Test Nonnuclear ABM," *Aviation Week*, Jan 24, 1983, p. 31, states that the flight vector of SRHIT was to be controlled by one hundred small rocket thrusters that formed a belt around the missile.

55. "Army/LTV Missile Intercepts Reentry Vehicle," *Aviation Week*, Jul 14, 1986, p. 119.

56. Office of Assistant Secretary of Defense (Public Affairs), "Experimental Flight Vehicle Destroys Moving Target during Experiment," News Release 325–86, Jul 1, 1986.

57. See note 55 above.

58. U.S. Army Strategic Defense Command, Public Affairs Office, FLAGE Fact Sheet, Apr 1991; Office of Assistant Secretary of Defense (Public Affairs), "Experimental Flight Vehicle Destroys Moving Target during Experiment," News Release 325–86, Jul 1, 1986.

59. Intvw, Raymond R. Ross II with Dr. Donald R. Baucom, the Pentagon, Washington, D.C., Sep 11, 1992, p. 10.

60. U.S. Army Strategic Defense Command, Public Affairs Office, FLAGE Fact Sheet, Apr 1991; Assistant Secretary of Defense (Public Affairs), "SDI-Related Test Intercepts Tactical Missile," News Release 268–87, May 22, 1987.

61. U.S. Army Strategic Defense Command, Public Affairs Office, FLAGE Fact Sheet, Apr 1991; "ERINT Shatters Warhead in Second Successful Intercept," *BMD Monitor*, Feb 25, 1994, p. 74.

62. "ERINT Shatters Warhead," p. 75.

63. *Ibid.,*

64. Fuller quoted in Hughes, "Patriot PAC–3," pp. 59, 61.

65. "ERINT Shatters Warhead," p. 75.

66. David Hughes, "Army Selects ERINT Pending Pentagon Review," *Aviation Week*, Feb 21, 1994, p. 93; U.S. Army Program Executive Office, Missile Defense, Public Affairs Office, Redstone Arsenal, Ala., "ERINT Intercept—Memorandum for Correspondents," n.d., provided Feb 15, 1994, by BMDO's Maj. Christine Queen.

67. Hunley, "The Enigma of Robert H. Goddard," p. 332, sees this facet of Goddard's method as being part of an American tradition. Thus, Hunley wrote:

> Goddard was born in Worcester on October 5, 1882, to a family of modest means but with deep roots in the rocky New England soil. His father, Nahum Danford Goddard, was a minor inventor who encouraged Robert's early inclination toward experimentation and invention both directly and by example. Nahum also inculcated in his son the notion that it was better to work for himself than for someone else and that it was advisable to mind his own business rather than to interfere in the concerns of others. Because of Nahum's business interests and his wife's diagnosis as tubercular in 1898, the family moved back and forth between the industrial city of Worcester and Boston, about forty miles to the east. Living in Worcester appears to have been influential in Robert's development because the city's glorification of individual inventors like Eli Whitney and Ichabod Washburn helped stimulate the young man to become an inventor himself. In the process, he got so concerned about patenting and protecting his inventions . . . that he became unusually secretive.

68. For information on the rise of command technology, see William H. McNeill, *The Pursuit of Power: Technology, Armed Force, and Society Since A.D. 1000* (Chicago: University of Chicago Press, 1982), pp. 173–176, 278–279, 331, 357–360; Walter A. McDougall, . . . *the Heavens and the Earth: A Political History of the Space Age* (New York: Basic Books, Inc., 1985), p. 5. Thomas P. Hughes, *American Genesis: A Century of Invention and Technological Enthusiasm, 1870–1970* (New York: Viking, 1989), p. 353, had this to say about the roots of command technology in the United States: " The prowess of the independent inventors, the well-publicized achievements of the industrial research laboratories, and the organization and management of large systems of production spread the belief that America could invent and produce its future by design."

69. Winter, *Rockets into Space*, p. 52. I found no mention of Goddard having seen a

complete V–2 in *Papers of Goddard*, Vol. III, pp. 1577–1609, which covers the period in Goddard's life from March 1, 1945, until his death on August 10. There are grounds for concluding that Goddard believed the Germans had stolen his design. On December 28, 1944, he completed an eight-point comparison between the V–2 and his own rocket design, concluding that the design of the two was virtually identical. (Vol. III, p. 1556) There is also reason for believing that Goddard may have felt that the government's refusal to support his efforts denied him the opportunity to develop a rocket as capable as the V–2. In 1940 and 1941, Goddard and his major supporter Harry F. Guggenheim had tried to persuade the Army and Navy and others of the importance of the rockets Goddard had been developing. Guggenheim offered the federal government the use of the facilities his foundation's grants had developed at Roswell, New Mexico, along with the services of Goddard and three machinists. This was to be at no cost to the government. This proved impossible to arrange, although the Army and Navy reached a contract agreement for the use of these facilities to develop a jet-assisted takeoff system for aircraft. These arrangements were made toward the end of 1941. During this time, little or no interest was expressed in long-range rockets. (See *Papers of Goddard*, Vol. III, pp. 1311, 1313, 1314, 1409, 1432–1437.) Shortly before the United States entered World War II, Goddard was concerned that the Germans might be developing long-range rockets. See *Papers of Goddard,* Vol. III, 1334—the document here is a Jul 10, 1940, letter from Goddard to Wallace W. Atwood. Evidently, when Goddard first began working for the government in World War II, at least two of his rockets were flight-tested before the "shop force" was put to work on other Army and Navy problems. Of this Goddard wrote later: "Reason for no action by the military on long-range rocket in 1940: the liquid-fuel rocket discussed was for use in comparatively large sizes and for relatively long periods, hence more suitable for long-range rather than short-range rockets. The United States had no need for long-range rockets at that time." (Vol. III, 1558) That Goddard examined parts of V–2s is noted in several places. In fact, at the request of the Navy, Goddard wrote a detailed evaluation of the V–2's pump (see Vol. III, p. 1598). For other mentions of the V–2 in this time frame, see Vol. III, pp. 1582, 1583, 1598.

The Satellite—
From Definite Possibility to Absolute Necessity: Five Decades of Technological Change

Rick W. Sturdevant

Satellite technology has changed remarkably over the past fifty years. The hardware has advanced from mere ideas to complex machines. Organizational structures have evolved from a research and development (R&D) focus to an operational one. As evidenced by annual appropriations, support for space programs has waxed and waned. The basic functional areas envisioned for satellites have remained consistent over five decades, even though one—a dedicated military manned spaceflight capability—went unfulfilled. Meanwhile, the capabilities of space systems have proliferated to meet an expanding variety of conflicts. Initially, the U.S. military dominated space activities, and civil (including scientific) space programs often served the Cold War objective of enhancing national prestige. More recently, however, burgeoning commercial and international activities have added new dimensions of complexity to the space arena. Given such trends, no simple recitation of changes in satellite *hardware* can adequately explain advances in the *technology*.

Rather, several interrelated elements have significantly influenced the rate at which satellite technology has advanced. Those elements include, but are not necessarily limited to, technical capabilities as manifested in material products; leadership; policies, procedures, and processes as reflected in management approaches and organizational forms; supportive networks or coalitions; a certain rhetoric; crises; priorities; funding; and goals or objectives. Taken together, such elements constitute a social construction of satellite technology.[1] Defining the technology in this way helps us explain how and why it grew in infancy from ideas akin to those of science fiction to become in its maturity a bulwark of U.S. military, economic, and political security. Understanding this might help us gauge the prospects for further development at the dawn of the twenty-first century.

Technical Capabilities

Technical capabilities certainly rank high in any assessment of technological advance. On November 7, 1944, Gen. Henry H. "Hap" Arnold, Army

Air Forces (AAF) chief of staff, directed Dr. Theodore von Kármán, director of both California Institute of Technology's Jet Propulsion Laboratory in Pasadena and the newly formed AAF Scientific Advisory Group in Washington, D.C., to prepare a survey that could become a guide for the AAF's future research and development program. In his first formal report to Arnold on August 22, 1945, von Kármán stated that further V–2 development would make it possible to launch missiles that would achieve speeds of 17,000 mph or more, which is orbital velocity.[2] That report, titled "Where We Stand," became part of a multiauthored, multivolume survey called *Toward New Horizons*, which von Kármán delivered to Arnold on December 15, 1945. In his introduction, titled "Science, the Key to Air Supremacy," von Kármán briefly addressed German V–2 rocket development and concluded, "The 'satellite' is a definite possibility."[3] Less than six months later, on May 2, 1946, RAND's seminal engineering report on the "Preliminary Design of an Experimental World-Circling Spaceship" proclaimed the feasibility of satellites. RAND said the Air Force could produce a successful booster-satellite combination within the limits of existing technology, given $150 million and five years' time.[4]

Uncertainty about the nation's technical ability to field an operational long-range rocket for launching warheads or satellites caused development schedules to lengthen. The decision to fund only research and development of major components, not entire rocket or satellite systems, tended to retard the rate of overall technological advance during the early 1950s.[5] The same was true for satellites, which moved little beyond the paper-study stage until 1956, and even then most people were concerned exclusively with full-scale development for reconnaissance purposes.[6] Not until the mid-1960s through the early 1970s did most other types of military satellite systems become operational. The latter systems subsequently tended to evolve block-by-block as technical improvements became possible, and that "block" approach to the upgrade of existing operational systems continues with even the newer satellites like the Global Positioning System (GPS) and the Military Strategic and Tactical Relay Satellite (Milstar). This approach advances the technology with less risk, less R&D time, and less cost than fielding entirely new systems every dozen or so years.

Advancement of technical capabilities in other fields sometimes has spurred change in space technology. The ability to significantly reduce the size and weight of nuclear weapons rendered long-range rockets, the type that could be used for spacelift, more immediately useful. Solid-state electronics, printed circuits, microchips, and the appearance of ever smaller, more powerful computers had an almost incalculable effect on satellite development. Weight and volume reductions resulting from nanotechnology have rendered plausible the satellite-on-a-chip concept. Progress in propellant chemistry has given more boost per pound. Technical advances in power-generation hardware, especially those associated with collecting and storing solar energy, proved vital to extending the life and overall performance of satellites. Recent successes with ion propulsion offer the prospect of increasing satellite longevity by an order of magnitude.[7] Metallurgy and, more recently, the burgeoning study of composite materials have contributed to lighter, cheaper spacecraft. Frequently, industrial laboratories or commercially sponsored academic research facilities have led these kinds of technical improvements.

This recognition led the authors of *New World Vistas* to conclude in December 1995 that the Air Force had to abandon the old perspective that large-scale, government-funded R&D programs would push military satellite technology forward. The space technology volume of the *New World Vistas* survey of air and space power for the twenty-first century emphasized "cross-cutting technologies" for spacecraft manufacturing and operation that will be developed commercially and will pull military satellite technology forward. Furthermore, the report concluded that "the Air Force's hierarchy of preference in acquiring space capabilities should be to buy commercial services where possible" unless some compelling reason exists to augment commercial systems with military capabilities or employ dedicated military systems.[8] This does not mean the Air Force should cease its own efforts to advance satellite technology; it does mean those efforts might shrink significantly to focus on the sort of high-risk, high-payoff R&D programs that commercial interests find too uncertain.

During January 1998, the Air Force Research Laboratory at Wright-Patterson Air Force Base, Ohio, sponsored industry briefings in Atlanta and San Francisco on a new Dual Use Technology Development Program. Aimed at leveraging commercial industries to obtain new products or process technologies with potential applications in both military and commercial sectors, this program sought to accomplish what *New World Vistas* had recommended. Technical topics for fiscal year 1998 included ground-based imaging and inspection of orbiting satellites; rocket-based, combined-cycle engine technology; upper-stage nozzle integration for medium-lift, expendable launch vehicles; low-power electronics for space; and a common interface between spacecraft and spacelift vehicles. Bidders on any of those projects had to bear at least 50 percent of the total cost of the proposed effort. They also were required to present the Air Force with a convincing description of how the developed product or process would enter the commercial marketplace.

Leadership

The presence of influential leaders tended to promote more rapid technological advance. A particularly stellar constellation of individuals appeared in the military, government, industry, and academia during the late 1940s and rose to high positions of responsibility throughout the 1950s and into the early 1960s. In January 1945, "Hap" Arnold appointed Maj. Gen. Curtis E. LeMay as first Air Staff Deputy Chief of Staff for Research and Development. Although that position lacked sufficiently broad powers of supervision to draw together the AAF's diverse R&D activities, LeMay succeeded in creating two very important institutions: the Air Force Institute of Technology and, with Frank Collbohm's help, the Research and Development Corporation (RAND). The latter's May 1946 report and its subsequent studies identified potential uses, both military and scientific, for a satellite vehicle and set the stage for Air Force Vice Chief of Staff Gen. Hoyt S. Vandenberg's approval in January 1948 of a policy statement asserting that "The USAF . . . has logical responsibility for the Satellite."

During this same period, a small group of so-called Young Turks or Junior Indians led by Lt. Gen. Donald L. Putt further advanced the concept of a partnership among science, industry, and the military as the best way to stay in the technological race. Seeking more autonomy for R&D within the Air Force, the Young Turks sought to establish an R&D command and implement a systems approach to R&D in which specialized task forces would be assigned to particular weapon systems or components. An Air Research and Development Command, albeit with strong ties to Air Materiel Command, was finally created on January 23, 1950. Those ties ultimately would prove too binding, which led to their severance and establishment of Air Force Systems Command (AFSC) on April 1, 1961. Instrumental in that organizational transition was Gen. Bernard A. Schriever, who in 1954 had played a starring role in implementing the Teapot Committee's recommendations as first commander of Western Development Division (WDD).

The organizational forms that worked so well for space-system R&D and the fielding of the first operational satellites proved incapable of effectively expanding the usefulness of those satellites to warfighters in the air, on land, and at sea. A group of younger officers commonly known as space cadets found themselves making increasingly shrill calls during the late 1970s and early 1980s for establishment of a major command for space operations. Through the efforts of Col. Thomas S. Moorman, Jr., and others, the Air Force created such a command on September 1, 1982. To further promote the U.S. military's commitment to making satellites an integral part of war planning and war fighting, the Department of Defense (DOD) established the joint United States Space Command three years later with separate Air Force, Navy, and Army space commands as its components. Despite these changes, the institutionalized momentum of the Systems Command bureaucracy delayed the transfer of such basic functions as satellite control and space launch to Air Force Space Command until 1987 and 1990, respectively. This almost certainly retarded efforts to normalize space operations within the Air Force as a first step toward integrating them with other facets of war planning and war fighting.

After the Persian Gulf War in early 1991, Air Force leaders, with Moorman in the forefront, began to seriously address the question of how satellites might more fully, and directly, aid the warfighter and what could be done to better educate senior field officers in all the services about the usefulness of space systems. A result of their deliberations was the establishment of the Space Warfare Center at Falcon AFB, Colorado, in November 1993. Further demonstration of Air Force senior leaders' commitment to space technology came in October 1996 at their Corona Fall meeting, where they acknowledged the Air Force is really an air and space force that will become a space and air force early in the next century.

Policies, Processes, and Procedures

General Schriever and his fellow innovators introduced processes, procedures, and policies that encouraged a somewhat revolutionary approach to development through centralized organizational structure at a time when many others believed technical limitations and financial constraints dictated a more traditional, evolutionary approach. To develop and field long-range missiles as quickly as possible, Schriever relied on the programmatic concepts of concurrency and parallel development that had proved so reliable during the Manhattan Project of World War II. Parallel development involved designing and building two different ICBMs simultaneously, which stimulated competition to produce a missile in the shortest possible time and, because each major subsystem of the two different missiles had different associate contractors, provided insurance against failure of a single contractor. Concurrency aimed to save valuable time by having missiles, sites, equipment, and trained crews all ready simultaneously, but it drove costs significantly upward.[9] Using these techniques, which amounted to a systems rather than a functional approach, it took just three years to design and build a successful Atlas; the Titan took slightly more than a year longer. In addition, the Gillette Procedures, which were announced on November 8, 1955, simplified administrative channels by cutting through unnecessary bureaucratic red tape and allowing both the WDD commander and Ramo-Wooldridge Corporation officials, the system integrators, to go directly to the Air Force's senior leaders.[10]

President Eisenhower's assignment in February 1958 of the highest and equal national priority to the development of Atlas, Titan, Thor, and Jupiter missiles and reconnaissance satellites signaled a "primary policy" stance. Breaking with past decisions and perspectives, the nation's senior leadership set in motion organized, innovative efforts to find a long-term solution to a specific, serious problem, i.e., the threat to national security posed by the Soviet Union's demonstrated capability to launch long-range missiles and space vehicles. This meant relatively easy access to, and strong support from, the sources of political, economic, and technical power. Although rapid technological change resulted for a few years, success and shifting priorities soon relegated development of military space systems to an ancillary position on the national agenda. Consequently, pathbreaking leaps gave way to incremental changes in the technology; clearly defined, long-range goals tended to blur in favor of narrower, short-range objectives. Politics rather than substantive issues or problems tended to drive decisions about Air Force space programs after the mid-1960s, and managing the growth of military space technology gave way to controlling it.[11]

The innovative management processes and procedures used by Schriever and his people for the early ICBM and satellite programs proved remarkably effective. One-time leader of AFSC Gen. Robert T. Marsh described a "very interesting historical paradox," however, when other people attempted to document what had been done in so-called procedural volumes, which ultimately became the Air Force–wide 375-series regulations and DOD directives on program management. Institutionalization of the procedures removed their flexibility, made them more obstructive than beneficial, and ultimately forced their abolition. Based on that experience, which illustrates people's propensity to "institutionalize almost anything that comes along," General Schriever has remarked that any *good* management approach lasts only five years, seven at most, before it succumbs to bureaucratization and should be scrapped for something new.[12]

No fundamentally new approach to the acquisition of military space systems occurred until the 1990s. Escalating development and procurement costs compelled the Air Force in early 1994 to seek centralization of all defense-related space requirements. Air Force officials argued that because multiple acquisition agencies had led to expensive, less effective capabilities, all military space acquisitions should be centralized. That initiative helped crystallize efforts to provide new, more effective organizational changes for military space. By the summer of 1995, DOD had created a Deputy Under Secretary of Defense for Space, established a Joint Space Management Board to coordinate activities between the Pentagon and CIA, and designated a DOD Space Architect. The last became responsible for ensuring compatibility and smooth operations among different military and commercial systems. Although occupied by an Air Force officer, the Space Architect position remained within DOD's joint structure.[13]

Further restructuring of the Pentagon's space policymaking function occurred on June 1, 1998. Based on guidance in the 1997 Defense Reform Initiative and extensive discussions between Gen. Howell M. Estes III, Commander in Chief, United States Space Command, and Keith Hall, Director, National Reconnaissance Office (NRO), the DOD decided to merge high-level management of classified and unclassified satellite systems. The Deputy Under Secretary of Defense for Space was disbanded; a newly established Deputy Assistant Secretary of Defense for Command, Control, Communications, Intelligence, Surveillance and Reconnaissance (C^3ISR) and Space Systems became the singular national security space architect. Skeptics viewed this change as evidence of space officials' declining influence in the Pentagon bureaucracy, but advocates saw it as a significant step toward cost-effective, procedurally beneficial integration of the traditionally separate worlds of "black" and "white" space.[14]

Meanwhile, the earlier effort at reforming policies and procedures to encourage innovative acquisition approaches showed signs of success. Program officers for GPS used performance-based specifications and best commercial practices to slice two years from the cycle time for the acquisition of Block IIF satellites, saved $1.1 billion, and reduced project manpower requirements by 38 percent. Another acquisition success story appeared to be the "high" portion of the Space-Based Infrared System (SBIRS) to augment and ultimately replace Defense Support Program (DSP) satellites for missile warning and missile defense. Total life-cycle costs were projected to be less than DSP because of smaller launch vehicles, reliance on a commercial spacecraft bus, and use of the cost as an independent variable technique to determine the best-value approach to meeting users' requirements. To bridge the gap between evolving space requirements and available budgets, it seemed almost certain that DOD should institutionalize its pursuit of acquisition reform.[15]

Support Networks and Rhetorical Strategies

A large-scale technology such as space systems advances more rapidly if supported by a strong network of relationships or a coalition of actors that uses a certain rhetoric of technology to win and sustain support.[16] The secrecy of the Cold War period undoubtedly prevented the Air Force from using some of the rhetorical strategies that might have achieved more cohesive coalitions and broader acceptance of its technological goals. National security considerations prevented the Air Force from publicly touting its Defense Meteorological Satellite Program (DMSP) in the way the National Aeronautics and Space Administration (NASA) promoted its weather satellites. The latter's rhetoric of long-range forecasts or extended prediction drew developers and users under a common banner, and successful storm warnings dramatically presented with pictures on television screens across the country encouraged broad-based public support for further government expenditures on Metsat technology.

Not until the 1990s did the Air Force experience the benefits of a similar rhetorical strategy. The stunning success of satellite early warning systems in detecting Iraqi Scud missile launches during the 1991 Persian Gulf War and the subsequent decision to declassify much DSP material gave the Air Force an opportunity to broaden its network of support for military space systems. When the service campaigned openly for a new SBIRS to improve on DSP capabilities, an informed segment of the American public rallied to space-based warning, national missile defense, and protection against limited strikes. Others supported space-based warning after learning that DSP could detect such man-made disasters as the oil-field fires set by Saddam Hussein's troops. Even more possibilities for expanding the network of military space supporters arose in February 1995 with declassification of America's first photographic reconnaissance satellite system, the Corona project. Release of the Corona archives gave geographers and environmentalists detailed images of natural and man-made topographical changes going back a dozen years prior to anything they had previously collected. Many Americans saw clearly that even highly classified military space systems ultimately had dual-use—additional civil or commercial—applications.[17]

Historically, the Air Force and other military services cooperated minimally to advance satellite technology. Interservice rivalry during the late 1940s and 1950s might have spurred the Air Force to develop its own space program more vigorously than if there had been no competition, but that same rivalry contributed to President Eisenhower's negative view of costly military space efforts. The president's attitude, of course, led to his support for creation of that thorn in the Air Force's side, the Advanced Research Projects Agency, to oversee development of military space systems, and the preeminent NASA to handle the nation's civil space program. Even though responsibility for acquiring all military space systems resided with the Air Force after the early 1960s, both the Navy and Army jealously preserved and protected their respective interests in space technology. Over the years, the Air Force definitely established strong ties and nurtured a common language among itself, defense contractors, and academic research institutions; it also cultivated support from certain congressmen and administration officials. Nonetheless, interservice rivalry frequently prevented the military services from assembling the sort of coalition and adopting the kind of rhetoric that would have made it easier to "sell" continuous improvement of military space capabilities to DOD, the President, the Congress, and the American people.

In the case of at least one specific type of satellite, the GPS, the President's science adviser simply deemed it too hard to build a supportive coalition. Over a quarter-century ago, Ivan Getting went to science adviser Lee DuBridge to enlist the latter's support for development of satellite navigation. Getting reasoned that a presidential commission might enlist support from many potential users: the Coast Guard, Air/Sea Rescue, the Air Force, the Navy, the Army, and foreign countries. After waiting approximately one month, Getting revisited DuBridge to see if there had been any progress. The science adviser said, "Well, I thought about it and decided it was too hard to get from here to there. There are too many people, too many bureaucracies, too much politics, and too many agencies involved. Why don't you just have the Air Force develop it the way we always did?"[18] The Air Force did precisely that and completed a fully operational 24-satellite GPS constellation on March 9, 1994.

Ironically, the rhetoric that might have built a coalition to develop GPS arose after the fact to support sustainment and improvement of Navsat capabilities. The system receives thunderous plaudits from all corners of the globe—hikers seeking to find their way in the wilderness, soldiers needing to fix their location on the trackless desert sands of Southwest Asia, commercial transporters tracking company vehicles on their delivery runs, military pilots pursuing targets on the ground or in the air, rental-car drivers seeking directions in a strange city, and operators of large computer systems that require precise timing to prevent crashes—the litany seems never to end. In the May 22, 1997, issue of *USA Today*, for example, an article waxes eloquent about how sports fishermen are benefiting from the "recent marriage of fish finders and GPS" and concludes that "it is a necessity."[19] This illustrates the importance of what one group of authors has described as "cross-cultural cooperation among varying space sectors, each with different goals, objectives, and interests" working in an atmosphere of trust and shared "space literacy" to achieve something mutually beneficial.[20]

It has not been, and never will be, easy to create and sustain viable coalitions for the advancement of space technology, but an attempt to do this becomes increasingly necessary as the national government seeks, and most Americans apparently favor, a balanced budget. One very strong signal that Air Force leaders recognize the importance of building coalitions and devising a rhetoric to sustain them was a joint announcement in April 1997 by Gen. Howell M. Estes III, Commander of Air Force Space Command, and Daniel Goldin, Administrator of NASA. They pledged that their organizations would cooperatively seek areas where sharing technical information, avoiding duplication of effort, and planning joint ventures might save money. Space Command people are working very closely with NASA, Lockheed Martin, and other contractors to explore the suitability of the X–33 VentureStar or something similar for manned military space missions early in the twenty-first century. A strong coalition among supporters of the X–33 increases the probability of bringing that program to fruition and of finally giving the Air Force the manned spaceflight capability it was unable to achieve through decades of fruitless, single-handed campaigning on its own behalf. Discussions between General Estes and Keith Hall during 1997–1998 committed their organizations to a heightened level of cooperation in space ventures.

Prospects for maintaining viable coalitions have improved considerably as a consequence of the Air Force's increasing reliance on both the civil and commercial space sectors. On May 29, 1998, the Air Force transferred management of its DMSP satellites to the National Oceanic and Atmospheric Administration (NOAA). That coalition, which resulted from a May 1994 White House directive to merge civil and military weather satellite systems, also involved NASA for the purpose of developing future systems. The goal was convergence of all U.S. weather satellites into a single National Polar-Orbiting Operational Environmental Satellite System early in the twenty-first century.[21] In another departure from decades of tradition, on August 5, 1997, the Air Force awarded its first satellite-imaging contract based on commercial off-the-shelf technology. Plans called for Orbital Sciences Corporation to piggyback the Warfighter–1 technology demonstration on its *OrbView–3* satellite, thereby reducing the project cost by 75 percent. The contract required Orbital Sciences to develop a mobile ground station for reception of satellite data and to provide software for both processing the hyperspectral data and assessing its tactical utility.[22] A broader community of interest—hence, a larger base of support for the advancement of space-based capabilities—could result from such ventures.

Crises and Priorities

A crisis atmosphere, particularly in the international arena, can accelerate the rate of technological advance by focusing the attention of congressional and high-level administration officials on a particular problem or threat. This certainly was the case in late 1953 when Professor John von Neumann's Strategic Missiles Evaluation Group, or Teapot Committee, chartered by Assistant Secretary of the Air Force for Research and Development Trevor Gardner pondered the increasingly probable development of an intercontinental ballistic missile threat from the Soviet Union. These fears led the Teapot Committee to recommend in February 1954 that development of an ICBM by the United States should be a matter of the highest national priority, not simply because it was technically feasible, but because advances in nuclear warhead development rendered such a missile useful as a delivery vehicle. President Eisenhower did, in fact, assign highest national priority to ICBM development on September 13, 1955.[23]

It took more than two years and another crisis, the launch of *Sputnik* on October 4, 1957, to gain equal status for Weapon System (WS) 117L, the Advanced Reconnaissance [Satellite] System. Finally, on February 3, 1958, Eisenhower gave highest and equal materiel priority to the Atlas, Titan, Thor, and Jupiter missiles; the WS–117L satellite; and the WS–224A (Ballistic Missile Early-Warning System) early-warning radar network.[24] A further sense of crisis surrounded fears that it was only a matter of time before the Soviet Union would be able to shoot down U–2 spy planes, and that spurred a fierce effort to launch a reconnaissance satellite via the Discoverer program at the earliest possible date. Of course, that date proved to be barely more than 100 days after Gary Powers' U–2 went down.

No comparable sense of crisis has emerged since that time to fuel demands for new satellite capabilities. The United States first used satellites militarily for meteorological and communications purposes during the Vietnam War, relied on them extensively for command and control during the Granada invasion (Urgent Fury) in 1983 and Panama operations (Just Cause) in 1989–1990, and extensively integrated space assets into theater operations for the first time during the Persian Gulf War (Desert Storm). While those experiences proved invaluable to advancing space technology from an applications or "user" perspective, they did little to promote the need for fundamentally different kinds of space-based capability. President Ronald Reagan's administration did its best during the 1980s to justify the Strategic Defense Initiative as something urgently needed to thwart sinister communist plots against the free world, but the sense of crisis never reached fever pitch and quickly disappeared with collapse of the Soviet Union in the early 1990s. Some might warn that terrorist groups or rogue nations pose a major threat, others might quake at the thought of an asteroid or comet colliding with Earth, but few people seem bothered enough by these things to label them an earth-shattering crisis.

If anything currently on the horizon could generate a sense of impending crisis, it might be a realization that the booming commercial space market and the looming international space sector pose serious questions about the future role of military space. Keith Calhoun-Senghor, Director, Commerce Department Office of Air and Space Commercialization, observed recently that global competition, technical advances, and a loosening of Cold War governmental restrictions are causing commercial space investment to rapidly outpace government spending. Annual revenues from commercial GPS applications are expected to surpass $8 billion by the year 2000, and those from satellite imagery should top $1.2 billion. When one includes satellite communications, total space industry revenues should exceed $100 billion annually within the next two years. These developments lend credibility to the comparison some military experts have drawn between freedom of the seas and freedom of access to space. In the future, preservation of our national security almost certainly will depend on our ability to exercise military space power to protect U.S. and allied commercial or civil satellites. The effective exercise of such power requires development of affordable access to space and new space-based military capabilities.[25]

Funding

Highest-priority designation allowed WS–117L program managers to finally obtain more funding. The level of funding, as well as the consistency of funding, for both long-range missile and satellite programs initially had been much less than desirable. A $1.4 million contract awarded by the AAF to Convair in April 1946 resulted in the MX–774 rocket, but sharp reductions in development funds led to cancellation of the contractual agreement in July 1947. The MX–774 program was cancelled entirely in February 1949, only to be resurrected as the MX–1593 Atlas program in January 1951 when the Korean conflict prompted an increase in military spending. General Schriever recalled that, as late as 1957, he had to campaign relentlessly before he finally convinced Secretary of the Air Force Donald Quarles to give a scant $10 million for satellite development. By comparison, the ICBM development budget for that year expanded to $491.5 million within a total ballistic missile budget of $1,135 billion.[26] Some even have argued that the "inadequate initial funding" which the Air Research and Development Center allotted WS–117L "ultimately resulted in the preeminence of civilian managers of U.S. satellite observation systems."[27]

Funding levels supported relatively steady development and fielding of operational satellite systems during the 1960s and 1970s. From the mid-1980s onward, however, planners could not rely on similar good fortune. Fluctuating annual appropriations threatened to reduce the size of the 24-satellite GPS constellation and probably contributed to AFSC's decision during the prototype stage to trim communication links in the commanding network to a level that proved inadequate once the system became fully operational. An unsteady funding profile lengthened Milstar's development schedule and forced cutbacks in the satellite's technical capabilities. Efforts to secure sufficient money for a follow-on to DSP were repeatedly rebuffed within the corridors of the Pentagon or the halls of Congress. Not until the spectacular performance of DSP in the Persian Gulf War, the resulting ground swell of support for ballistic missile defense, and marriage of "Star Wars" technical capabilities with existing infrared techniques did the Air Force gain approval and funds to acquire a new SBIRS.

While the amount and steadiness of funding over time can dramatically affect how long it takes to develop and field space-related systems, decisions on how the Air Force should invest available dollars are also important. Larry Lynn, director of the Defense Advanced Research Projects Agency observed in March 1997 that government should "invest in the highest-payoff technologies and military concepts—even when technical risk would inhibit others."[28] When declining budgets compel the military services to trim significantly their force structures, expenditures for research and development of new systems should focus selectively on whatever maximizes the capability of a smaller force to respond to the full range of future conflicts. Space systems, particularly those with dual-use applications that benefit both military and civilian sectors, can do precisely that sort of thing. Secretary of the Air Force Sheila Widnall should have surprised no one, therefore, when she commented in April 1997 that "our satellites on orbit increased by 250 percent" at the same time that fighter and bomber forces declined by 50 percent and overall Air Force budget and personnel cuts amounted to 40 percent.[29] Military space advocates cannot rest easy, however, because they too are being forced to choose among programs, rather than finding ways to fund all of them.[30]

Goals or Objectives

A final factor in the advancement of satellite technology is whether well-defined purposes, objectives, or goals drive the technology, or if the opposite prevails—technology drives the goals. The pursuit of rocket systems to launch nuclear warheads across intercontinental distances and reconnaissance satellites into space was a clearly stated objective during the 1950s. In subsequent decades, however, it became obvious that military satellites for other purposes, such as communications and meteorology, were being developed and launched without a precise understanding of how they might be employed in a conflict. With the end of the Cold War, satellites like DSP and Milstar that had been intended for strategic purposes suddenly had to be justified on the basis of tactical requirements. Among the reasons that the Air Force never managed to achieve a manned spaceflight capability for itself is that the purpose could not be defined clearly enough to justify the expense within the context of national space policy. It always has been more difficult to convince Congress and the President to spend money on hardware for which the purpose is unclear, and it becomes almost impossible during a fiscally tightfisted era. If we discover new applications for existing satellite systems, that constitutes technological advancement, but we can no longer afford new, technologically advanced systems for which the purpose is initially unclear.

Based on this survey of elements that contribute to technological change, it seems that periods of especially rapid advance occur under a particularly ideal set of circumstances. Technical capabilities must already be adequate to the task at hand. Strong, dynamic advocates must be present within the military, government, industry, and frequently, academia. A certain rhetoric of technology must exist to help assemble and sustain coalitions of support for large-scale space programs. Innovative and effective policies, procedures, and processes, as reflected in management approaches and organizational forms, must exist and be suitable to the task at hand. Funding must be at least minimally sufficient in amount and steadiness to meet the existing development schedule. Finally, urgency spawned by a sense of crisis elevates the priority accorded the technology.

These elements seem to have come together in an especially strong way only twice during the last fifty years, and when they did, satellite technology advanced at a much faster, more dramatic pace. The first time the elements conjoined ideally was during the middle 1950s to the early 1960s when they served to hasten the advance of the satellite from the status of a definite possibility to that of reality. A strong case might be made that these conditions resurfaced, perhaps with somewhat less intensity and clarity, during the late 1980s and 1990s. United Nations forces were so reliant on satellite systems during the Persian Gulf conflict that Chief of Staff of the Air Force Gen. Merrill McPeak called it the first space war. As the United States withdrew its forces from more and more overseas locations, cut the total force structure dramatically, and still sought to maintain a capability to project its military might whenever and wherever needed, space-based assets became an essential part of the strategic equation. They gave the nation a global presence that could, hopefully, preserve the peace by deterring potential aggressors who knew they were being watched and would be held accountable for their actions; in the event conflict did occur, satellites would contribute mightily to a more efficient, effective deployment of air, sea, and land forces. By the mid-1990s, the Air Force acknowledged that "technology today has evolved to the point that using space is essential to victory on the battlefield."[31] Looking ahead, Air Force leaders recognized that "space power" would evolve from its role of supporting forces in other media—land power, sea power, and air power—to become a separate and equal medium itself—space power.[32] The satellite had become an absolute necessity for military operations.

Military history informs us that when conflict arises it is best if we already have the required technology in place. Indeed, having the technology in place (as in the case of nuclear weaponry) might even deter potential aggressors and prevent war. Unfortunately, military leaders have focused almost habitually on preparing to avoid the mistakes of the previous conflict rather than anticipating the challenges of the next one. This means great advancements in the technology needed to deter or defeat aggressors generally await the propelling circumstances of an international crisis, which we might prefer not to experience. For this reason, the visionary perspective of current Air Force leaders on space technology is especially significant. It amounts to a clarion call, in a noncrisis environment, for rapid advancement of the technology needed to ensure America's dominance of near-Earth space. How successful they will be in achieving their objective remains to be seen.

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